

VOLUME I

annual progress report

AUTOMOTIVE LIGHTWEIGHTING MATERIALS

FREEDOMCAR AND VEHICLE TECHNOLOGIES PROGRAM

*Less dependence on foreign oil today, and transition
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U.S. Department of Energy
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**U.S. Department of Energy
Office of Vehicle Technologies
1000 Independence Avenue S.W.
Washington, DC 20585-0121**

FY 2006

**Progress Report for Automotive Lightweighting Materials
Volume I**

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October 2007

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1. INTRODUCTION

Automotive Lightweighting Materials R&D

As a major component of the U.S. Department of Energy's (DOE's) FreedomCAR and Vehicle Technologies (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.

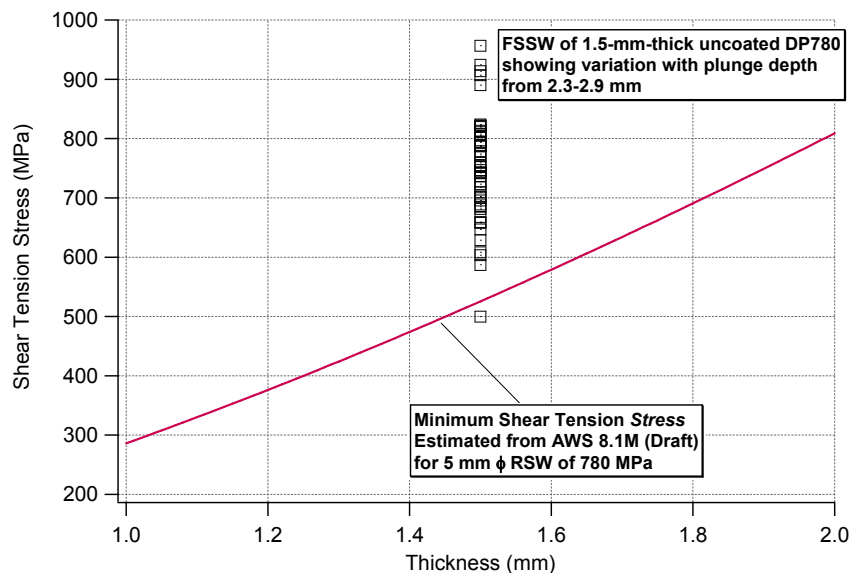


Figure 1. Data plot showing the variation of shear tension stress with DP780 sheet thickness. Data points indicate that intrinsic strength of FSSWs can exceed minimum specified for RSWs.

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.

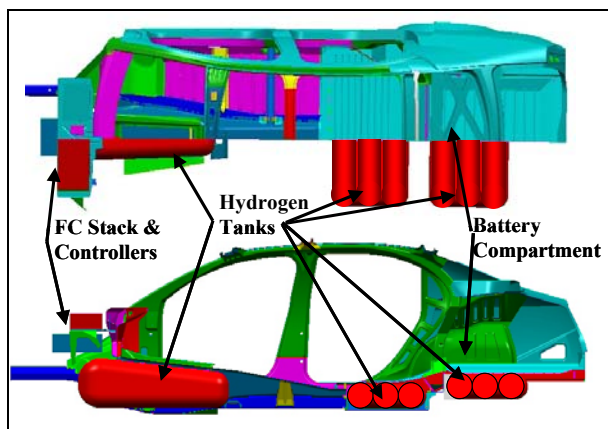


Figure 2. Optimized AHSS solution.

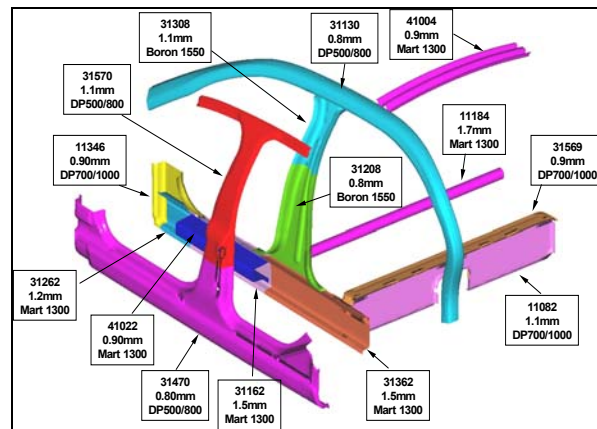


Figure 3. Fuel-cell powertrain components comprehended.

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 inner 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. *Phase 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.

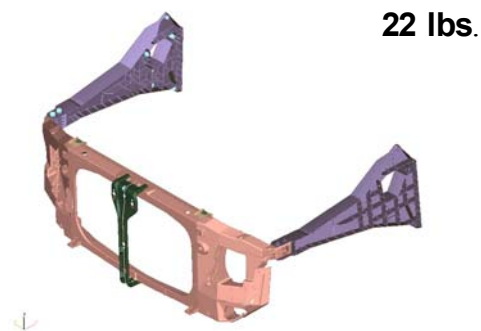


Figure 7. ULC Cast magnesium front-end proposal (68% lower weight).

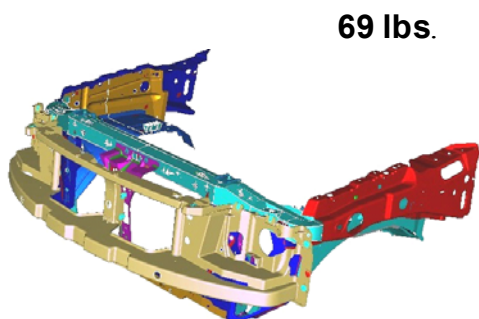


Figure 8. Conventional steel front end structure (2006 Ford Expedition).

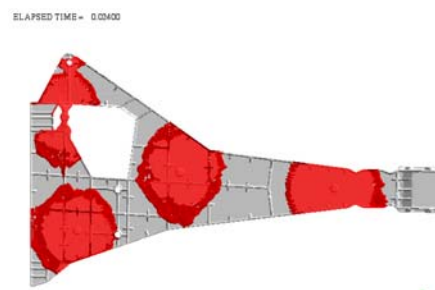


Figure 9. Example of flow simulation and filling pattern for hot runners.

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 preforms 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.

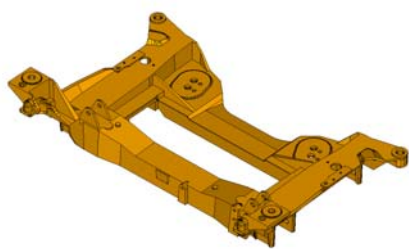


Figure 12. Image of magnesium front engine cradle.



Figure 13. 2006 Corvette.

Argonne has successfully produced recovered plastics, at least polypropylene/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.

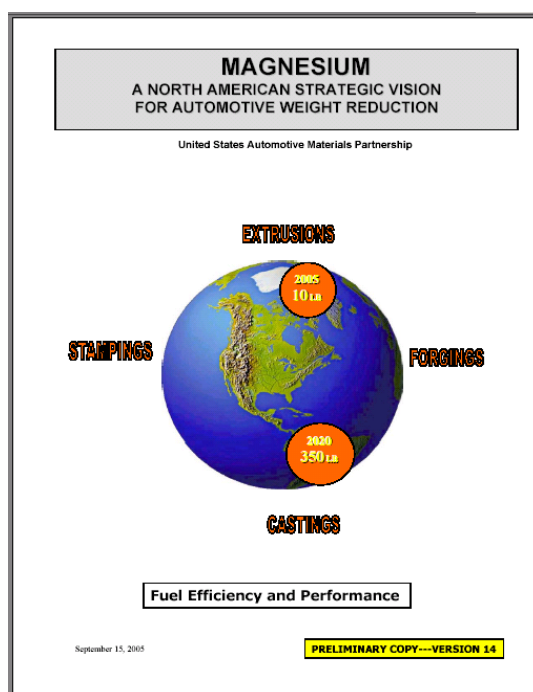


Figure 14. Cover of USAMP strategic vision for automotive Mg through 2020.

2. AUTOMOTIVE METALS

A. Warm Forming of Aluminum II (AMD 307¹)

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Contract No.: FC26-02OR22910

Objective

- This project previously demonstrated the potential of warm-forming (WF) technology to significantly improve the formability of aluminum. The Phase I demonstration was done in “prototype” mode and demonstrated the expanded depth of draw that is possible with WF. The objective of Phase II is to develop and demonstrate a production process for the WF of aluminum for automotive body structures and measure the economic feasibility of the WF process for a production environment.

Approach

- Develop individual elements of the WF process in a laboratory environment including alloy characterization, lubricant development, forming simulation and process thermal modeling.
- Develop full-size demonstration of WF process and run tests in a production-like environment. Process will include blank preheating, lubricant application, WF press and die with modified thermal profile controls, and lubricant removal.
- Create a technical cost model that can generate cost comparisons between a warm-formed aluminum door inner and a same or similar door inner manufactured using conventional forming processes in steel and aluminum.
- Significant improvements in the formability of aluminum are expected to be achieved through development of enabling WF process advancements including:
 - Establishing the degree of improvement in formability of production-grade, commercial aluminum alloys.
 - Developing a cleanable lubricant suitable for use in a WF process.
 - Optimizing the temperature distribution of the die for improved thermal control and formability.
 - Evaluating rapid preheating systems for blanks.
 - Applying CAE simulation tools (finite element analysis) to modify the die to attain a production-quality part.
 - Optimizing a process and layout design.
 - Applying the results of the cost model to optimize process design.
 - To demonstrate the manufacturing and economic feasibility for a new production process such as the WF process, the definition of the process flow is paramount, as well as the development and application of a technical cost model that allows comparison of a product made in the WF process with a comparable component fabricated from aluminum or steel using current stamping technology.

Accomplishments

- Successfully demonstrated the formability improvements that can be obtained by forming Al sheet at elevated temperatures.
- The purpose-built die ultimately designed and used in the Phase II study enabled a uniform and stable thermal condition. This also minimized distortion in the tool so that the binders remained relatively flat throughout the forming trials.
- Showed that commercial AA5182-O and AZ31B-O alloys could be formed at die temperatures above 300C to a full 125 mm depth.
- A forming window was defined which is bracketed at extremes in preheat temperature and high binder pressure by splitting, and at low binder pressure by wrinkling.
- The new WF lubricant performed very well in the current trials and should be viable for a high volume WF process.
- Formability increased with increasing die temperature; however, increasing blank preheat temperature above 350C did not necessarily improve formability.
- The binder load required to successfully make Mg parts was lower than that required for steel.

Future Direction

- This project is complete.
- A follow-on project focused on warm forming of magnesium sheet is beginning and will be reported on in the annual report for fiscal year 2007.

1.1 Objectives

Approved for incorporation into the USAMP/ AMD project portfolio in 2001 with completion in December 2006, the objectives of the AMD 307 Phase II project, Warm Forming of Aluminum II, were to develop and demonstrate:

- A full scale WF process for the forming of Al sheet for automotive body structures, and
- Determine the financial viability of the WF process for a production environment using a technical cost model.

1.2 Phase II Technical Approach

The previous WF study was sponsored by PNGV and completed in 2000 as part of the Automotive Lightweighting Materials program. That Phase I study demonstrated the concept feasibility of WF technology to significantly improve the formability of Al using a specially-processed 5000 series Al alloy containing Mn and Mg. The Phase I study used a Conventional stamping die retrofitted with heaters thought to be sufficient for use in WF (Figure 1).

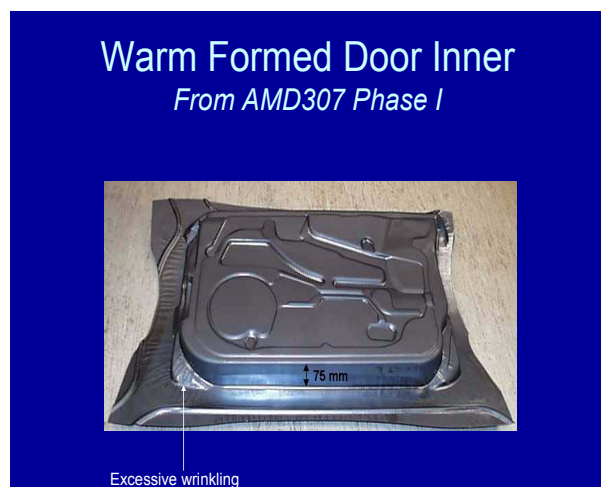


Figure 1. Warm formed door inner made in Phase I die showing excessive wrinkling and sheet distortion.

The Phase II technical approach used was designed to first experiment and to test the capabilities of various process components in a laboratory environment before scale-up to a press-shop-type process demonstration. The technical approach was to:

- Develop and evaluate individual elements of the WF process first in a laboratory environment including alloy characterization, forming lubricants, forming simulations, and process thermal modeling.
- Develop full-size demonstration of WF process and run test trials in a press-shop environment. Process design included planning for blank pre-heating, lubricant application, press and die with WF thermal controls and identification of lubricant removal strategies.
- Create a technical cost model that can be used to generate cost comparisons between a warm-formed, deep-drawn Al part and a same or similar part manufactured using conventional forming processes in steel or other alloys.

Phase II Accomplishments

Significant improvements in the formability of production grade, commercial Al alloys, specifically AA5182-O, were achieved through development of WF process advancements in Phase II as discussed below:

- **Constitutive equation** was developed for AA5182-O for formability simulations that allowed design of WF pan die and definition of WF process parameters.
- **Cleanable lubricant** suitable for use in a WF process was identified through extensive laboratory-based studies of multiple lubricant formulations. Lubricant application and friction trials were conducted and the best performing lubricant, Fuchs 216 BN, was selected for WF trials.
- **Rapid conduction preheating system** for blanks was designed in Phase II that would enable cycle times of 6-10 jobs/minute. However, the project budget proved insufficient to build a full-scale preheater and material handling automation. A conventional conduction oven was made available to preheat the blanks for the WF trials and the blanks were moved manually, thereby allowing the project to remain within budget.
- **WF trials** were initially conducted in November 2005, utilizing the Phase I door inner die that was modified in Phase II to the maximum extent possible, in an attempt to achieve thermal control over die regions and components.

Knowledge gained from these first trials reaffirmed the viability of a WF process, but conclusively proved that a controlled WF process cannot be achieved using a conventional stamping die refitted with heaters, as was the door inner die shown in Figure 2.



Figure 2. The conventional stamping die refitted for the WF feasibility study performed in Phase I.

- **Purpose-built WF pan die** was designed using CAE simulation tools (finite element analysis) and knowledge gained from monitoring and analyzing thermal behaviors during the door inner WF trials utilizing the modified Phase I die. This purpose-built pan die provided thermal stability and uniformity (See Figure 3).
- **WF pan die trials** conducted in October 2006 allowed optimized process parameter monitoring and control. Forming was conducted using four different thermal conditions: room temperature, entire die at 250C, binder at 300C with the punch at 250C, and entire die at 350C. Full pans, 125 mm deep, were stamped at the latter two conditions without splitting or wrinkling. Trials were performed to understand the effect of blank preheat temperature and lubricant type as well as to provide a preliminary understanding into the performance of Mg sheet.
- **Technical cost model** was developed and used to evaluate and optimize the Phase II process design and to compare process cost of WF of Al parts to similar parts fabricated in steel by conventional stamping methods. The model can be applied to future process designs.



(a)



(b)

Figure 3. (a) Photograph of the WF pan die used in Phase II study and (b) typical pan produced by the die.

Conclusions

The WF pan die trials conducted in October 2006 successfully demonstrated the formability improvements that can be obtained by forming Al sheet at elevated temperatures. Blanks were preheated externally from the die prior to forming, traditional press speeds were used, and a complex die temperature control / monitoring system was used to understand and control the thermal conditions in the tool. This enabled forming windows to be identified wherein successful WF could be performed. It also enabled comparison of lubricants and various materials. Some specific conclusions are:

1. The purpose-built die ultimately designed and used in the Phase II study enabled a uniform and stable thermal condition. This also minimized distortion in the tool so that the binders

- remained relatively flat throughout the forming trials.
2. Commercial AA5182-O and AZ31B-O alloys could be formed to a full 125 mm depth at die temperatures above 300C.
 3. A forming window was defined which is bracketed at extremes in preheat temperature and high binder pressure by splitting, and at low binder pressure by wrinkling.
 4. The new WF lubricant performed very well in the current trials and should be viable for a high volume WF process.
 5. Formability increased with increasing die temperature, however, increasing blank preheat temperature above 350C did not necessarily improve formability.
 6. The binder load required to successfully make Mg parts was lower than that required for steel.

¹ Denotes project 307 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.

B. Active Flexible-Binder Control System for Robust Stamping (AMD 301¹)

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Contract No.: FC26-02OR22910

Objective

- Develop and demonstrate, on an industrial scale, an optimized, closed-loop, flexible-binder control system that can be installed in presses to improve the quality, reduce the variability, and maintain the accuracy of stampings made from aluminum alloys and ultra-high-strength and stainless steels. The system will also reduce cost for developing and setting production tools.

Approach

- Conduct open-loop control demonstration of flexible-binder technology.
- Develop methodology and guidelines for designing and building flexible binders.
- Develop computer simulation and process optimization capabilities for flexible binders.
- Develop a closed-loop, flexible-binder control system with appropriate sensors.
- Demonstrate closed-loop control of the flexible-binder system on industrial parts.
- Evaluate the technical and economic feasibility of flexible-binder technology.

Accomplishments

- A multi-point cushion system with 26 independently-controlled hydraulic cylinders was used to demonstrate flexible-binder control technology on a full-size General Motors (GM) liftgate inner. The system enabled the stamping of liftgate panels from three different sheet metal alloys (A6111T-4, bake-hardenable (BH) 210 and dual-phase (DP) 500) and various thicknesses (0.7-1.0 mm). This was accomplished by implementing appropriate binder load trajectories for each material using software-based adjustments without the need to modify or adjust the stamping tools.
- Completed trials and demonstration on the GM liftgate inner using optimized binder-force trajectories that varied in location and stroke. The demonstration showed that finite-element analysis (FEA)-based optimization

can provide effective initial settings for tonnages and these settings can be easily modified to obtain good parts. In addition, shop-floor press operators ran the software and demonstrated that the user interface with the system has minimal operational complexity.

- The system reduced the die-tryout time by about 80%. Splits and wrinkles could be eliminated or reduced in minutes by adjusting the tonnages of the appropriate cylinders.
- Conducted closed-loop trials and demonstration in a mechanical press using a new, 10-cylinder, binder-load control unit with large pan tooling. The unit was equipped with feedback control system and wrinkle-height sensors.
- Assessed the room-temperature forming of magnesium (Mg) alloys. Conducted stamping tryouts of the GM liftgate inner using Mg alloy AZ31B.
- Demonstrated the binder-load control unit with the rigid wheelhouse tooling.
- Reviewed manufacturing benefits and value of flexible-binder control technology.

Future Direction

There is some discussion on the course of future work with respect to performing die work. One approach is that the die should receive minimal work before the maximum benefit of changing cylinder loads is evaluated with the die in the "as cut" condition. An alternative approach is that the die should be worked to produce as good a panel as possible without the use of cylinder-load variation, and the cylinders would then be used only to improve the part as much as possible. The final strategy will need to be resolved before pursuing implementation and commercialization of this technology.

A number of steps must be taken before all the benefits of this technology can be brought to the production readiness stage:

- Design, build and test a movable, multi-point cushion system that can be used with various dies to produce different parts. Hydraulic cylinders should be capable of re-configuration in space to accommodate various part shapes and geometries.
- Design, build and test more efficient valves and controllers.
- Design and build a more efficient and simplified hydraulic system to circulate oil.
- Develop efficient, closed-loop process controllers for friction and draw-in sensors.
- Conduct a full-scale economic feasibility study of this technology.
- Develop efficient simulation/optimization codes to reduce computing time for load-trajectory optimization.
- Develop criteria for best application of the technology (type of parts and presses).
- Develop plans to integrate this technology into the stamping plant.
- Involve leading press manufacturers in developing, retrofitting, integrating and implementing hydraulic cushions in their presses.

Introduction

Significant effort is spent on fine tuning dies to eliminate wrinkles or splits in formed panels. Fine tuning the die is an iterative process of welding, grinding, polishing and testing to produce defect-free parts. This process is disruptive, time consuming, frustrating and expensive. Also, there is an increasing demand for using lightweight materials in the transportation industry; however,

such materials are less formable than the low-carbon steel that they are replacing. This has pushed the stamping industry to consider alternative methods to forming lightweight and high-specific-strength materials. Recently, innovative binder concepts with optimized computer simulation and advanced press controls have led to the development of flexible-binder load-control systems. Such systems can be built and installed in existing mechanical presses to allow better control of the forming process.

A hydraulic cushion unit consisting of 26 independently-controlled hydraulic cylinders with liftgate tooling was built and successfully installed in a mechanical press to produce panels from different sheet metal using the same set of tools. Binder-force trajectories generated by both trial-and-error and FEA simulation were implemented and liftgate panels from BH210, DP500 and A6111-T4 were successfully made. The tryout time using the system was considerably less than that using the conventional method of working the die. Stamping trials have shown that the new flexible-binder control technology can improve part quality, enhance process robustness, and reduce the time and cost for die tryout and fine tuning. The ability of binder-load control technology to influence manufacturability using a rigid wheelhouse die was also demonstrated.

Computer Simulation and Optimization

Traditionally, the binder force is applied uniformly on the binder surface and held constant during the forming process. Also, the magnitude of the binder force for a given part is determined based on past experience and trial and error. Many studies have shown that variable binder-force trajectories increase the formability and improve dimensional accuracy of stamped complex parts. Hydraulic cushions with programmable multi-pins are commercially available on some mechanical transfer presses, but programming such pins proved to be challenging for press users. Currently, such presses are set up using extensive trial and error that results in long tie-ups of those presses.

An optimization algorithm was developed and implemented in the simulation code to predict optimum constant and variable binder-force trajectories in multi-point cushion systems. Computer simulation was successfully used to determine the temporal and spatial binder-force trajectories for the flexible-binder with the liftgate tooling shown in Figure 1.

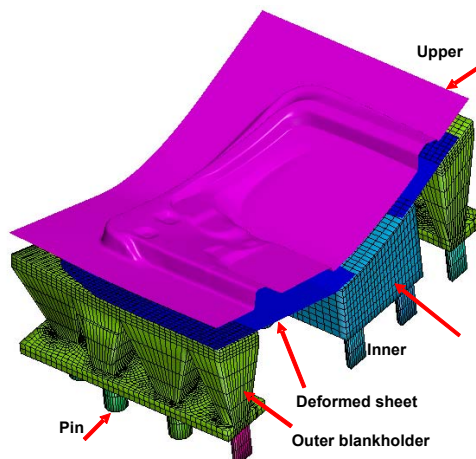


Figure 1. Finite-element modeling (FEM) model of flexible binder for the liftgate inner die.

Pin numbers and locations with respect to the liftgate simulation are shown in Figure 2. Due to symmetric boundary conditions, only 15 pins (pins 1- 15) were considered in the analysis. Finite-element (FE) simulations coupled with optimization techniques were used to estimate the optimal binder force required for each cushion pin to form the liftgate inner part. In this study, part thinning and wrinkling were the only parameters used to monitor part quality. The tolerable wrinkle amplitude was 0.05 mm. Wrinkles on the sidewall were not monitored because those wrinkles were found to be insensitive to the binder force.

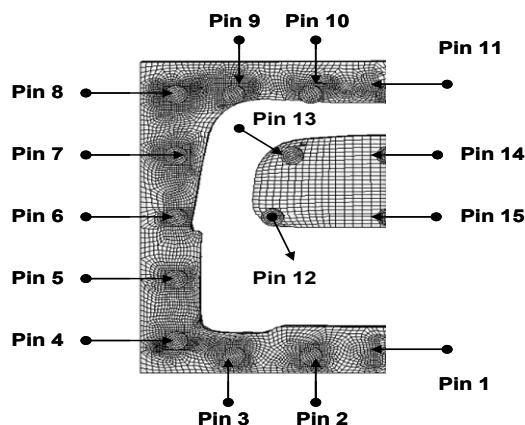


Figure 2. Pin numbers and locations in the liftgate simulation.

Three materials, 1) BH210 steel of thickness 0.818 mm, 2) Aluminum (Al) alloy A6111-T4 of thickness 0.998 mm and 3) DP500 steel of thickness 0.785 mm, were used to stamp liftgate inner panels. Different materials and thicknesses were selected to demonstrate that flexible-binder technology can accommodate variations in materials by simply adjusting the individual pin forces in the multi-point cushion system.

In multi-point cushion systems, four modes of applying binder forces on pins during the forming process are possible. Table 1 shows the effect of trajectory mode on maximum thinning in the simulated liftgate. Optimum binder-force trajectories for the four modes were predicted and analyzed.

Mode 1 and Mode 2 trajectories produced maximum thinning of 27% and 25%, respectively. Those strains were high enough to cause splits in the formed panels. Mode 3 and Mode 4 trajectories produced maximum strains of about 23%, which are still high but is less than those produced by trajectories of the other two modes.

Tryouts have shown that panels made by using Mode 3 and Mode 4 binder-force trajectories either had no splits or that the splits were corrected by slight trial-and-error adjustment of the pin forces in the flexible binder.

Table 1 also shows that there is no difference in the maximum thinning obtained by using either Mode 3 or Mode 4 trajectories. This apparent insensitivity to

Table 1. Effect of trajectory mode on maximum thinning in the simulated liftgate.

Trajectory Mode	Description	Maximum Thinning (%)
Mode 1	Pin forces constant in space and stroke	27
Mode 2	Pin forces constant in space and variable in stroke	25
Mode 3	Pin forces variable in space and constant in stroke	23
Mode 4	Pin forces variable in space and stroke	23

pin-force variation with stroke may be due to the inherent constraint/assumptions used in the optimization procedures.

Predicted optimized binder-force trajectories for Mode 3, variable in space but constant during the stroke, for A6111-T4, BH210 and DP500 are shown in Figure 3. It is interesting to see that the trajectory patterns for the three materials are similar. They only differ in the level of force applied on each pin. This force level follows the same pattern followed by the yield/tensile strength of those materials.

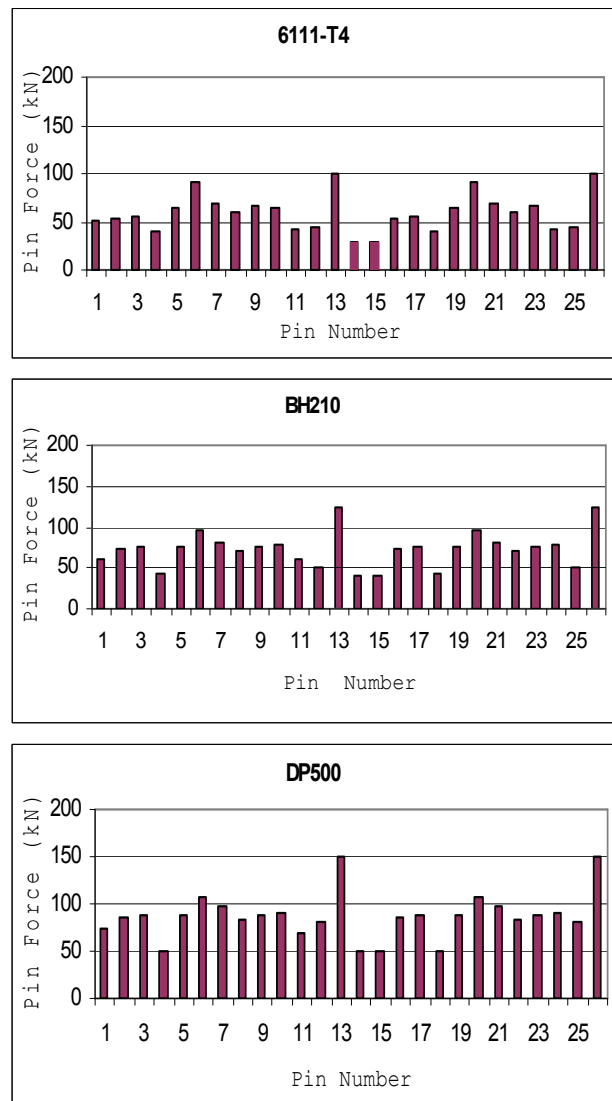


Figure 3. Predicted binder-force trajectories, variable in space but constant in stroke, for A6111-T4, BH210 and DP500.

Figure 4 shows two sets of predicted trajectories for A6111-T4 using the Mode 4 scheme. Set 1 was obtained using sequential optimization while set 2 resulted from using fixed-curve-shape optimization. The trajectories in set 1 start low and end up high while trajectories in set 2 start high, reach a minimum at a stroke of 40 mm, then increase gradually until the end of the stroke.

Set 1 produced panels with two splits in the window area that were corrected later by increasing pin forces in that location. Set 2 produced panels with splits above the liftgate window. No tryouts to fix those splits were attempted.

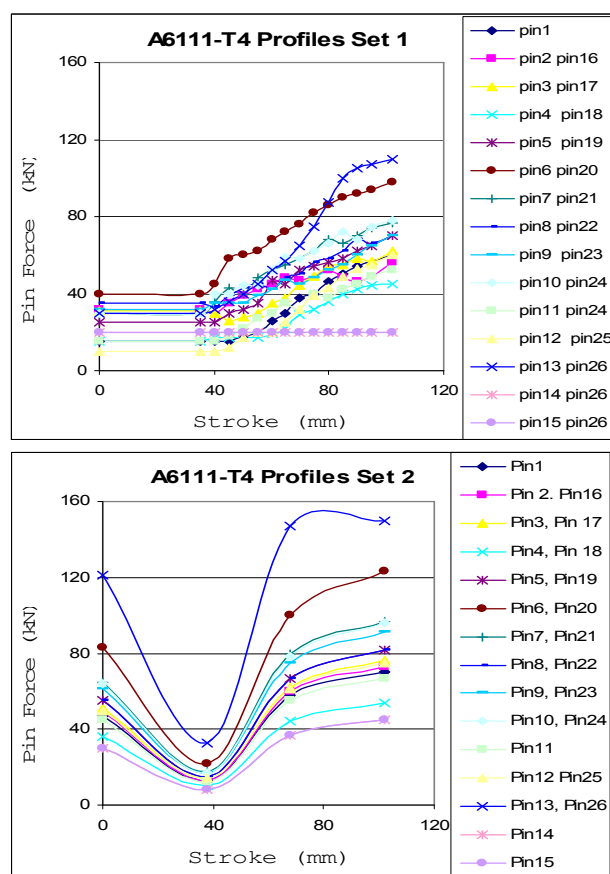


Figure 4. Predicted binder-force trajectories, variable in space and stroke, for A6111-T4.

Liftgate Tryouts and Demonstration

The 26-point, flexible-binder control unit with the liftgate tooling was installed in a mechanical press at Troy Design and Manufacturing (TDM) in Warren, Michigan and tested using both constant and variable binder-force trajectories. Liftgate panels

were successfully made from BH210, DP500 and A6111-T4 using the same set of tools.

Figure 5 shows an A6111-T4 blank geometry of 1 mm thickness used in the experiments/tryout. The edges of the blanks were deburred to avoid cracking during forming due to defects in blanking and piercing from the coil. The sheets were lubricated with dry thin-film lubricant precoated on the coil from the rolling mill.



Figure 5. Blank from A6111-T4 used in tryouts.

The tryout time using the system was less than the estimated tryout time using conventional methods of working the die. Splits could literally be eliminated in minutes by adjusting the tonnages of the appropriate cylinders.

Binder-force estimates from FEA were used for the initial tryout of A6111-T4. The liftgate panels were formed without splits (Figure 6). However, minor wrinkles were observed in the flange area beyond the drawbeads on the top and bottom and on one of the corners. Experiments carried out with very high binder force could not eliminate the wrinkles in the flange as observed in FEM simulation.

Figure 7 shows liftgate panels made from three materials: A6111-T4 (top), BH210 (middle) and DP500 (bottom).



Figure 6. Panels from using Mode 4 trajectory.



Figure 7. Liftgate panels made from A6111-T4, BH210 and DP500.

The A6111-T4 panels were made with Mode 3 and Mode 4 trajectories. Mode 3 trajectory formed the panel without splits on the first hit. Mode 4 trajectory formed the panel with splits (Figure 8 top) that were later eliminated by increasing force on specific pins in the last 12 mm of the stroke (Figure 8 bottom). BH210 panels were made with Mode 3 trajectory without any splits. DP500 panels were made using Mode 3 trajectory with splits in the window area that were later eliminated by using trial-and-error to setup appropriate pin-force trajectories.

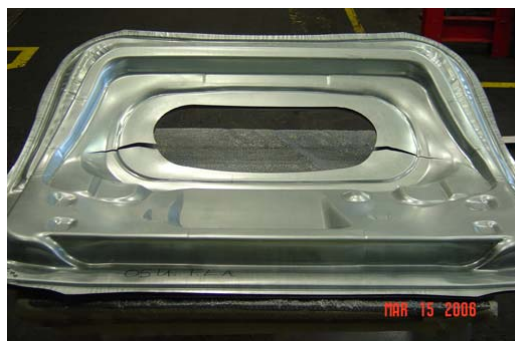


Figure 8. A6111-T4 liftgate panels formed with splits (top) and without splits (bottom).

Reproducibility tests were performed to evaluate the ability of the flexible-binder system to produce identical panels in consecutive hits. Ten panels were formed in sequence using the same binder-load trajectory and then checked for dimensional accuracy and thinning. Results indicated that the stamping process produced consistent panels.

Room-Temperature Forming of Mg Alloys

The use of sheet Mg alloys for auto-body applications is very limited because their room-temperature formabilities are low. Currently, Mg alloys can only be formed at elevated temperatures.

However, the introduction of new Mg sheet alloys AZ31B and ZK10 with improved room-temperature formability as well as the development of new methods for processing and stamping sheet metal, made it interesting to re-evaluate such alloys for room-temperature forming via flexible-binder control.

A. Viscous Pressure Bulge (VPB) Test of Mg Alloys

One of the objectives of this study is to conduct VPB tests on 1.3-mm-thick Mg sheet alloy AZ31B and 1.2-mm-thick Mg sheet alloy ZK10 to determine their room-temperature flow stress and formability. A schematic drawing for the VPB tooling is shown in Figure 9.

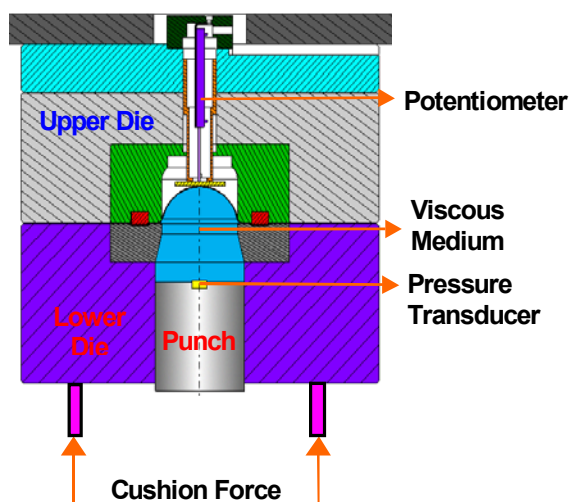


Figure 9. Schematic of the viscous pressure bulge (VPB) test.

In the VPB test, the pressure and the dome height would be used to estimate the flow stress of the material using inverse analysis. The dome height before the burst indicates the formability of the material. Five samples would be tested to check for consistency in the values obtained for flow stress and formability.

The first step in conducting the test is to clamp the sheet metal between the upper and the lower die. Doing this step with Mg alloys proved to be challenging. The sheet metal failed by brittle fracture at the lockbead location because the radius of the lockbead was too small for bending the

material. Figure 10 shows a AZ31B blank after being clamped.

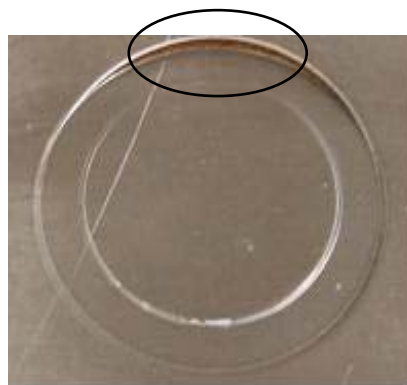


Figure 10. Brittle fracture at the lockbead location during the VPB test for AZ31B.

Because the lockbead in the tooling caused brittle fracture of the material in the test setup, it was later removed and the test was performed using a blank holder force of 500 kN. Figure 11 shows Mg sheet formed in the VPB test without using lockbead. This time, the sample failed due to brittle fracture at the die radius thus producing a very small dome height. This indicates that a die radius of 6.25 mm was just too small for successful bending of the Mg-alloy sheet material AZ31B.

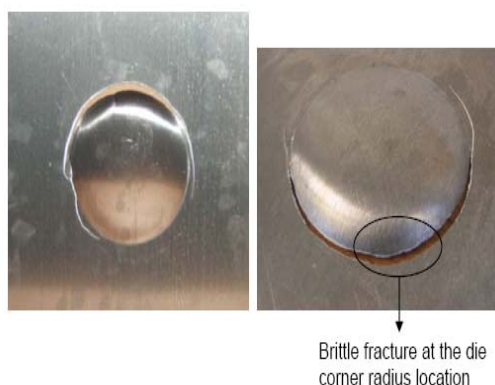


Figure 11. Magnesium alloy AZ31B formed in the VPB test without using lockbead.

To overcome the problem caused by the small die radius, another VPB test setup with a larger die radius of 30.4 mm and without lockbead was used. This time the magnesium sheet fractured at a dome height of ~13 mm.

Maximum achievable strain for Mg-alloy AZ31B, electrically-treated AZ31B and ZK10 was 0.05, 0.065 and 0.08, respectively, due to their small dome heights. A comparison of the dome height obtained from the test for different materials is shown in Figure 12. The results show that the dome height of magnesium alloys AZ31B and ZK10 are significantly lower than those for BH210, A6111-T4 and DP500, in spite of the fact that the die radius used for these materials was much smaller than that used for the Mg alloys.

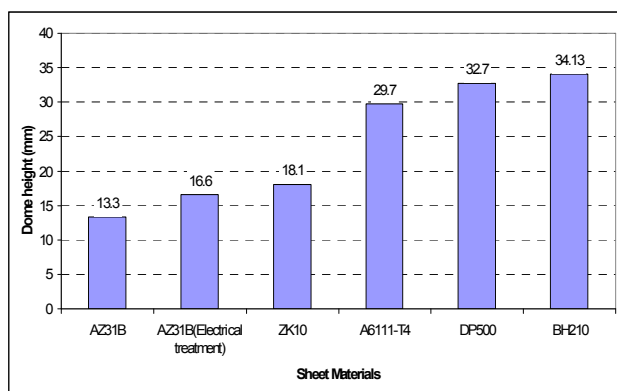


Figure 12. Comparison of the dome height obtained in VPB test for sheet materials A6111-T4, BH210, DP500, ZK10 and AZ31B.

The figure also shows that the maximum dome height before failure for AZ31B, electrically-treated AZ31B and ZK10 material was 13.3 mm, 16.6 mm and 18.1 mm, respectively, indicating very low formability for these materials at room temperature. Although electrical treatment for AZ31B improved its formability by increasing the dome height from 13.3 mm to 16.6 mm, it is still considered to be low in comparison to the dome heights of steel and Al alloy.

Figure 13 shows photos of the burst samples in the VPB test for A6111-T4, BH210, DP500 AZ31B and ZK10. Superimposed on the photos are measurements of the dome heights. The Mg alloys showed poor formability in spite of removing the drawbeads and using a larger die corner radius of 30.2 mm.

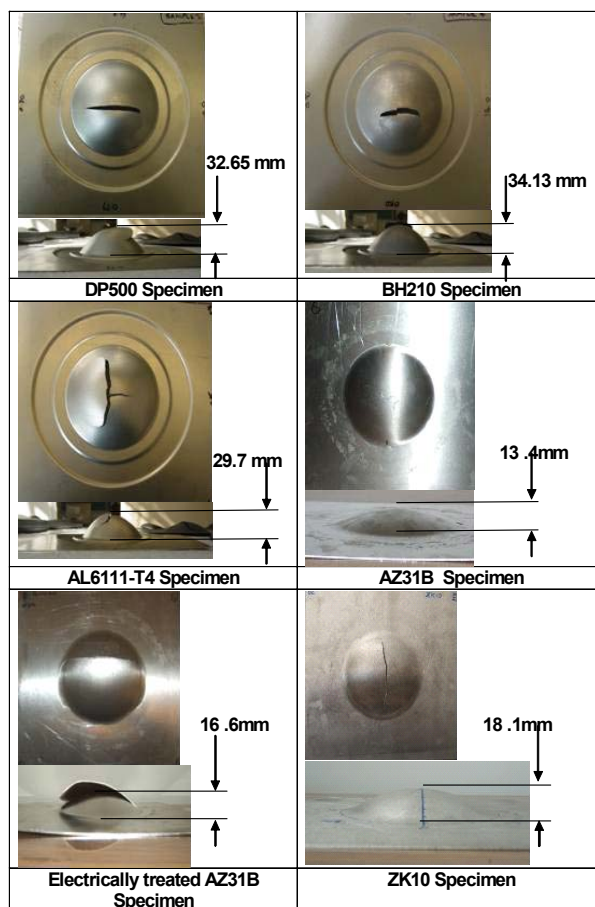


Figure 13. Comparison of the burst samples in VPB test at room temperature from sheet materials A6111-T4, BH210, DP500, AZ31B and ZK10.

B. Simulation of the VPB Test for Mg Alloys

The critical value of the effective strain that would result in brittle fracture of the AZ31B sheet material during bending was estimated from the VPB test. The maximum effective strain in the material at the fracture location could not be measured. Therefore, FE simulation of the test was conducted to predict the effective strain at the fracture location observed in the test. The maximum effective strain predicted by FE simulation for the dome height of 13.8 mm and forming pressure of 43 bars occurred at the die radius where fracture was observed in the experiment. The maximum strain due to stretching and bending at that location was 0.05. This value of strain would be used as a failure criterion for predicting brittle fracture during bending of AZ31B sheet material. The failure criterion was later used to check the feasibility of forming liftgate panels from the Mg alloy.

C. Simulation of the Mg Liftgate

The liftgate tooling was selected to check the possibility of forming sheet AZ31B at room temperature using the multi-point cushion system developed in this program. The same liftgate tool was used in the past to successfully stamp panels from A6111-T4, BH210 and DP500 sheet material.

FE simulation coupled with optimization was used to estimate the optimum binder-force trajectories needed to form the GM liftgate part from sheet AZ31B. The flow stress of the material was estimated from the VPB test and used as input for the FE simulation.

During the clamping stage of the forming simulation, the sheet metal bends and unbends at the upper and lower bead as shown in Figure 14. The bending deformation of the sheet metal is similar to that observed at the die radius in the VPB test where brittle fracture occurred. Therefore, in order to check for potential brittle fracture of the sheet metal at the location of bending in the liftgate drawbead, the predicted maximum effective strain at that location was compared with the critical value of 0.05 obtained from VPB test for the AZ31B.

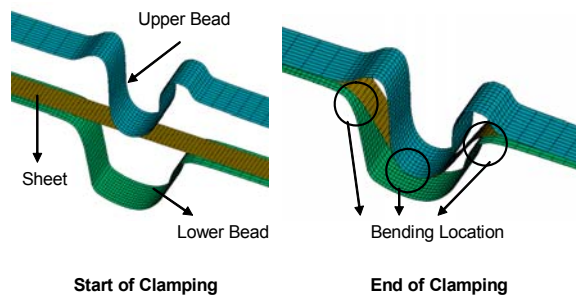


Figure 14. Drawbead simulation of the sheet at the start and end of the clamping.

In drawbeads, bending deformation is observed at three locations as shown in Figure 15. The predicted maximum effective strain in the drawbead was higher than the estimated critical value indicating potential failure of the sheet metal at the drawbead when the sheet is clamped.

Figure 15 simply suggests that the liftgate part would fail at the clamping stage and, therefore, the liftgate panel could not be formed from AZ31B

sheet material at room temperature using the existing tooling.

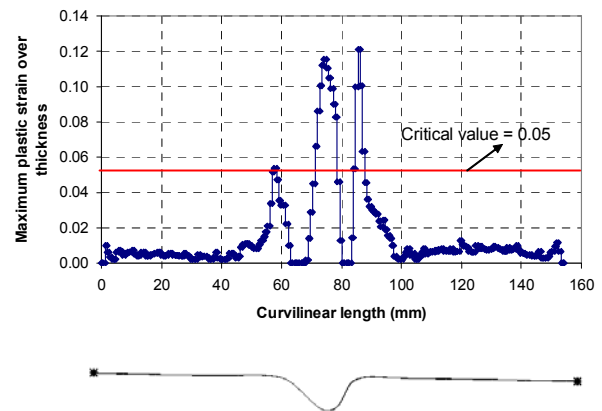


Figure 15. Maximum effective strain along the curvilinear length of the sheet at the end of clamping.

Because FE simulation predicted failure of the liftgate at the clamping stage, forming simulation of the part beyond clamping was found to be futile and, therefore, was not pursued. It was then decided to try forming the liftgate panel using die tryouts at TDM.

D. Tryouts on the Mg Liftgate

Several attempts were made to form liftgate parts from AZ31. Initially, based on FEA simulations, the tonnage in all cylinders was set to 5.1 tons. However, the material fractured upon bead set as seen in Figure 16. It is also noted that the fractures upon bead set in the tryouts were predicted by FEA analysis and also observed in biaxial tests. Following this tryout, another attempt was made to form the part with tonnages reduced to 1 ton through the stroke for all cylinders. In addition, the 404 lubricant typically used for Al was applied to the blank and the ram was set to cycle to 25 mm (1 in) off the bottom of the stroke. The outcome of this tryout was similar to the previous attempt.

Forming liftgate panels from these versions of magnesium alloys AZ31B and ZK10 at room temperature is not feasible. The alloys performed poorly in situations where sharp bends were involved. Although the formability of Mg alloys at room temperature is low compared to Al and steel, it may still be possible to stamp such materials into



Figure 16. Magnesium AZ31 liftgate trial with 404 lubricant and minimum tonnage.

simple shapes using flat binders. The application of an electric field during annealing of Mg alloys appears to increase their forming properties. The increase, however, is not sufficient to make Mg alloys formable at room temperature.

Pan Tryouts and IFU Unit Demonstration

A new 10-cylinder, binder-load control unit with pan tooling was built in Germany by a consortium which included the University of Stuttgart (IFU), MOOG, Hydac and the USCAR. The unit was tested successfully in a hydraulic press at the University of Stuttgart in Germany. The unit was shipped to the US in November 2005 for installation tryouts and demonstration in a mechanical press at the TDM facility in Warren, Michigan.

A. Control System Tests

IFU, with technical support from Hydac and Moog, ran tests to verify that the pressure control system can track all command trajectories. Figure 17 shows an example of a flawless tracking force-versus-stroke trajectory in cylinder #5 at a slide velocity of 300 mm/s. The actual value and the command signal for a rectangular force/stroke profile were almost identical.



Figure 17. Force-versus-stroke trajectory.

B. Closed-loop Tests

IFU and its partners performed tests on closed-loop control using wrinkle-height sensors. The tests were run with and without closed-loop control to show that the IFU unit can actually modulate the binder force in-process to produce wrinkle-free pans. The first set of tests was performed in Stuttgart using IFU's hydraulic press with a slide velocity of 20 mm/s. The test was initially run without activation of the closed-loop control system with the wrinkle-height sensor.

To produce wrinkles in a mild steel pan, a small binder force of 6 kN was applied to each of the six activated cylinders. This situation produced wrinkles so high (over 10 mm) that the drawing process had to be stopped at a depth of 100 mm for fear of damaging the die. In the second set of experiments, the 6 kN load was maintained on the six active cylinders, but this time the closed-loop control system was activated. A small, constant, wrinkle-height value of 6 mm was set as a limiting wrinkle height that should not be exceeded. The controller was successful in maintaining the imposed limit by modulating the binderforce on the six cylinders. Figures 18 and 19 clearly show that closed-loop control produces a significant improvement in the quality of the drawn pan.



Figure 18. Pan drawn without closed-loop control.



Figure 19. Pan drawn with closed-loop control.

A week-long demonstration of this technology was conducted on the IFU unit for project members, OEM personnel, DOE partners, suppliers, contractors, educators and students. The demonstration was intended to show the capabilities of flexible-binder technology and the benefits of using closed-loop control in the stamping process.

Wheelhouse Demonstration

The binder-load control unit was modified to accommodate the wheelhouse die to perform tryouts to evaluate the following:

- Springback Control
- Production Casting Flexibility
- Alternate Material Tryout
- Impact Tonnage Reduction
- Reduced Material Usage

The wheelhouse die, shown in Figure 20, was donated by Ford Motor Company. It was taken out

of production because the high-impact tonnage requirements caused damage to the stamping press.



Figure 20. Wheelhouse die.

Tests were conducted on production steel, BH, DP, and Al materials. Two trajectories were used, one with constant tonnage during stroke and the other with variable tonnage during stroke. Reduced-blank-size panels were also used. Parts were laser trimmed then scanned for comparisons using a current production draw panel as a reference material. The current rigid binder design was used for testing and single-cylinder pressure adjustments were made to show the ability of the binder to flex. Tryouts were conducted to show the capability of the binder-control unit to influence panel quality by creating or relieving fractures in the stamped part.

Test Results

- Proved the ability to influence part springback and splits through cylinder pressure adjustments.
- Proved flexibility of current production binder and its compatibility with variable- pressure technology.
- All tryout were completed without the use of “stand off” blocks on binder.
- Showed the ability to try out different materials and thicknesses by changing trajectories and without die hand work.
- Showed ability to reduce number of hits to achieve panels from difficult-to-form sheets.
- Reduced the impact tonnage from 274 tons with constant-stroke trajectory to 182 tons with variable-stroke trajectory.

- Test panels showed excessive springback with full blank but improved greatly with reduced blank panel with variable-stroke trajectory.
- Reduced blank weight by 15% and produced production-worthy stamping from production and BH materials using variable-pressure trajectories (Figure 21).
- Scans showed improved springback for reduced-size blanks that ran with variable trajectories.



Figure 21. Successful wheelhouse part with reduced production blank.

Technology Value

The ability to influence metal flow by simply changing pressure settings on individual cylinders very quickly replaced an estimated 4-8 hours of die work which would have been required, with traditional binders, to correct stamping defects in formed panels.

The value of flexible-binder load-control technology can be assessed in terms of improving manufacturing capability and adding robustness to the production system. The following are some of the manufacturing benefits achieved using this technology:

- Reduce die tryout and development time
- Reduce time to tune/spot binder
- Compensate for tool wear by adjusting binder-force during production
- Reduce tool re-work during production
- Improve part quality by providing optimum load trajectories
- Change pressure with stroke
- Control springback
- Stamp difficult-to-form materials
- Reverse pressure settings using software (unlike grinding and welding)
- Reduce blank size and save materials

There is a need to quantify the cost savings associated with these manufacturing benefits.

Conclusions

1. A multi-point cushion system with 26 independently-controlled hydraulic cylinders was used to demonstrate flexible-binder control technology on a full-size automotive part.
2. The system reduced the die rework time by about 80%.
3. Splits and wrinkles could be eliminated or reduced in minutes by adjusting the tonnages of the appropriate cylinders in the system software.
4. The system enabled the stamping of liftgate panels from three different materials and thicknesses. This was accomplished by implementing appropriate binder-load trajectories for each material without the need to modify or adjust the stamping tools.
5. FE simulation coupled with optimization technique was used to predict binder-force trajectories using four trajectory patterns. Best results were obtained for trajectories varying in space and constant in stroke for all the liftgate materials. Trajectories that vary in both space and time were not successful in producing defect free panels.
6. The demonstrations showed that FEA-based optimization can provide effective initial settings for tonnages and these settings can be easily modified to obtain good parts.
7. The capabilities of a 10-cylinder binder-load control unit with pan tooling and advanced controls was demonstrated at TDM.
8. Closed-loop tests show clearly that feedback control can produce a significant improvement in the quality of the pan.
9. System improved springback, reduced impact load and allowed the downsizing of blank.
10. Manufacturing benefits, value of technology and its implementation were reviewed.

Presentations and Publications

1. **Application of Flexible-binder Technology for Stamping of Liftgate Panels:**

Mahmoud Y. Demeri, Formsys Inc.

Presentation and publication at the International Conference on “New Developments in Sheet Metal Forming”, Stuttgart, Germany, May 9-10, 2006.

2. **Robust Deep Drawing Process of Extensive Car Body Panels:**

J. Hengelhaupt, M. Vulcan, IFU

P. Ganz and R. Schweizer, MOOG

F. Darm, Hydac

Presentation and publication at the International Conference on “New Developments in Sheet Metal Forming”, Stuttgart, Germany, May 9-10, 2006.

3. **Programming of Multi-Point Cushion Systems – Progress and Future:**

T. Altan and M. S. H. Palaniswamy, OSU

Presentation and publication at the International Conference on “New Developments in Sheet Metal Forming”, Stuttgart, Germany, May 9-10, 2006.

4. **Project Presentations:**

AMD Offsite Meeting, USCAR, October 27, 2005.

5. **Innovation in Stamping Technology:**

M. Y. Demeri, Formsys Inc.

Presentation at the International Congress TRANSFAC '06, San Sebastian, Spain October 4-6, 2006.

ⁱ Denotes project 301 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.

C. Die Face Engineering Project (DFEP) for Advanced Sheet Metal Forming (AMD 408ⁱ)

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Contract No.: DE-FC05-02OR22910

Objective

- The ultimate goal is to develop robust simulation technology to improve die design and die fabrication/processing so as to reduce manufacturing costs for all sheet-metal parts using lightweight metals such as advanced high-strength steels (AHSSs) and aluminum (Al). The project will demonstrate this goal by generating optimized sheet-stamping dies from computer-aided design (CAD) surfaces (from finite-element modeling (FEM) mesh) that compensate for springback while maintaining formability.
- The project will demonstrate that the simulation advances can eliminate the soft tool prototyping phase and, thereby, significantly reduce the die-tryout phase, with corresponding major reductions in costs and lead time for automotive components.

- The project deliverables include: (1) integrated product-process finite-element analysis (FEA) capability that will more accurately predict springback for both closures (>90%) and structural parts (~80%); (2) test results from simulations, panel trials and springback measurements that will be used to guide and validate the software development (done at private expense by vendors); and 3) capability to automatically and consistently generate a machinable CAD surface of acceptable quality from FEM meshes. The LS-DYNA engineering package is the team's preferred package for demonstrating the technology advances.

Approach

- The collaborating partners include Alcoa, DaimlerChrysler Corporation, Ford Motor Company/Volvo Cars Division, General Motors Corporation, US Steel, Livermore Software Technology Corporation (LSTC), and Technologies Research Corporation of the National Center for Manufacturing Sciences (TRC-NCMS) as Project Administrator.
- The approach has been to work with technology vendors and test laboratories to significantly improve the accuracy of material models for new high-strength, lightweight, sheet materials and to implement and validate the technology to analytically predict springback and formability for a broader range of closure and structural parts.
- The project tasks are being performed and reported in four main technology areas, and overseen by nominated expert team leaders:
 - A. Numerical Technology
 - B. Material Testing/Modeling
 - C. Field Validation
 - D. Surface Technology

Accomplishments

- Completed Springback Classification Study of closure and structural parts with information and results pooled from the DFEP team.
- Developed new algorithms (e.g., smooth contact) for better contact treatment and demonstrated improved stress calculation on benchmark parts that improves the efficiency and quality of springback predictions.
- Completed Common Die tryout experiments, and collected needed die and panel scan data for comparison to baseline forming and springback simulations.
- Completed Common Die baseline simulations using baseline FEM code and compared output with stamped AHSS and aluminum panels.
- Completed first-phase, mesh-to-surface morphing technology trials with three CAD vendors, and initiated second-phase improvement projects with one down-selected vendor.

Future Direction

- In the remaining project Year 3, an integrated product design-analysis-formability capability will be demonstrated that combines improved springback-simulation algorithms (material and surface contact) defined by the team and CAD-based die-face modification algorithms, which will be applied to the Common Die component geometry. A new die surface will be generated for tryout and a second set of structural panels formed and measured to validate the prediction and morphing technologies.
- A larger internal validation effort will be undertaken in Year 3 by the OEMs to industrialize "best practices" simulation standards and extend the integrated springback and CAD morphing technology to test additional challenging automotive parts.
- A cost-benefit analysis will be performed, comparing cost, quality and user-effort attributes of the improved simulation and tool-development capability with the conventional (baseline) die build and tryout process.

Introduction

Significant progress was made in this second year. To summarize, in Year 1, the DFEP team identified and classified part categories for which springback is still a challenge to predict (e.g., underbody parts), and then conducted new simulations utilizing significant LS-DYNA improvements (developed at vendor expense) and its linked modules. The end users tested these progressive numerical code enhancements, and identified the attributes of new material models (based on a literature study) needed to predict optimized tool geometry (in FEA mode) along with relevant sheet-material-formability process parameters. A Common Die structural rail geometry was selected to demonstrate technology advances.

In Project Year 2, several test laboratories were contracted to conduct measurements of critical formability and springback properties of AHSS and Al sheet materials being pursued for new vehicle lightweighting initiatives. Material properties determining isotropic and kinematic hardening, such as tension-compression, shear and bending-unbending, were measured and verified using the technical evaluation support of National Institute for Standards and Technology (NIST) experts. The resulting datasets were used to develop or refine several new material models for implementation in predictive computer-aided engineering (CAE) code.

Springback-prediction experiments were run to compare baseline simulations with experimental stamped panels of the Common Die part produced during initial die tryout. In addition, the DFEP team also collaborated with CAD software vendors to evaluate the feasibility of morphing directly from FEA meshes to smooth CAD surfaces. Six challenging automotive parts (two per OEM) with representative geometries were initially evaluated. Performance gaps in this technology were defined and improvement targets set for vendors to meet downstream numerical control (NC) surface-quality requirements.

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

Numerical Code Development:

- The DFEP Team conducted simulation experiments on an initial set of closure and structural parts to classify springback behavior, based on several end-user-defined computational and prediction-quality parameters. A consensus Springback Classification Table was developed that is being used to guide predictive-technology developments.
- Conducted extensive benchmark testing of new smooth-contact algorithms for improving geometric descriptions of the products and springback predictive accuracy in FEM. The effect of the number of elements on the tooling radius was studied using benchmark parts. Other studies have involved using different contact scale factors combined with initial coarse mesh, initial coarse mesh with smooth contact, and initial fine mesh with smooth contact.
- The team conducted modeling tests on a new element with improved through-thickness stress variations that may help improve springback prediction.
- Three new material models were formulated and implemented in the code with preliminary testing completed on benchmark parts.
- A follow-up study is underway to understand the impact of various numerical technologies on FEA computational efficiency and prediction accuracy. Different AHSS and Al sheet materials and binder forces have been used to test these new features on real production panel geometries.

Material Testing/Modeling

- Material modeling gap analysis and model development roadmap (prepared in Year 1) were used to drive new experiments and property measurement tasks in Year 2, in order to extract critical material parameters from data plots and to subsequently implement selected models into new FEM code. Candidate models included published, nonlinear, isotropic and kinematic hardening models such as the Chaboche, Vegter and Yoshida models.
- Material test laboratories in Poland, Germany and Japan (possessing domain expertise and proprietary test methodology or equipment)

were contracted for characterization, material testing and model fitting in order to develop a combined isotropic kinematic hardening model that (when implemented into numerical code) can significantly improve springback predictions.

Surface Development

The goal of the DFEP Surface technology development task is to assist the CAE/Stamping Development engineer to rapidly and robustly translate CAE die design (or modification information) directly into CAD data that can be used in machining dies. Year 2 highlights are discussed below.

- The DFEP team held individual technical reviews with each of three CAD vendors that performed Phase 1 morphing trials on six OEM-supplied component product data and target FEM meshes.
- Detailed mesh-to-CAD evaluation criteria were developed and a technical specification finalized.
- Based on the team's assessment of the most promising demonstrated morphing capability, in the second phase of CAD Surface R&D began in Year 2, the team worked with one down-selected vendor to continue more detailed evaluation of algorithmic, surface quality and computational efficiency improvements to commercial mesh-to-CAD software. Up to eleven parts will be tested in this phase. The goal is to develop NC quality die surfaces with minimum user intervention.

Field Validation

At the end of Year 1, a total of 36 Common Die (Figure 1) panels were formed at the team's die tryout facility for further study and specialized measurements in Year 2, including 9 gridded panels.

- The team completed strain reading of all 9 panels, followed by scanning of all draw panels, and then laser-trimmed selected panels for final springback measurements.
- Team members pooled the running of baseline LS-DYNA code and input decks to develop (for selected tryout cases) forming and simulation predictions, which were then compared with panel measurements.
- The team next plans to conduct simulations with the new code release on half-panels (Figure 2) to resolve discrepancies encountered in the comparison of scanned data to simulations.



Figure 1. Illustration of Common Die Panel, indicating 5 datum points.



Figure 2. Close-up of a half-sized D steel baseline panel formed on the Common Die.

ⁱ Denotes project 408 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.

D. Electromagnetic Forming of Aluminum Sheet

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Contractor: Pacific Northwest National Laboratory

Contract No.: DE-AC06-76RL01830

Objective

- The purpose of this project is to develop electromagnetic forming (EMF) technology that will enable the economic manufacture of automotive parts made from aluminum (AL) sheet. EMF is a desirable process because the dynamic nature of the deformation results in benefits which include increased forming limits and reduced springback. The benefits would result in increased use of Al and, therefore, more fuel-efficient vehicles due to mass reduction.

Approach

The project addresses three main technical areas:

- Analysis methods for forming-system design
- Development of durable actuators (coils)
- Industrial embodiment of the EMF process

Accomplishments

- Development of the flat-coil design
 - 1) Improvement has been made to both simplify and lower the cost of manufacturing flat coils;
 - 2) The packaging of the flat-coil assembly has been improved for robustness and ease of handling, and

- 3) A design was completed, and fabrication initiated, on a large prototype tool for EMF process demonstrations.
- 4) At PNNL, we upgraded the EMF capacitor-bank power-supply system to increase charge rate and decrease testing cycle time.
- Developed new, coupled, numerical models that describe three critical elements of the EMF process
 - 1) Propagation of the electromagnetic field through the coil-blank system and generation of pulsed electromagnetic pressure in specified areas,
 - 2) High-rate deformation of the blank and,
 - 3) Heat accumulation and transfer through the coil with an air-cooling system.
- Completed restrike simulation of an aluminum panel using a newly-developed flat concentrator.

Future Direction

- Complete automotive component tool development and fabrication, and demonstrate ability to form commercially-representative components.
- Develop further modeling capabilities that can assist in the design of EMF systems.
- Perform high-cycle-rate coil testing to demonstrate the commercial embodiment of EMF systems for automotive manufacturing.

Introduction

In the EMF process, a transient electrical pulse of high magnitude is sent through a specially designed forming coil by a low-inductance electric circuit. During the current pulse, the coil is surrounded by a strong, transient, magnetic field. The transient nature of the magnetic field induces current in a nearby conductive workpiece that flows opposite to the current in the coil. The coil and the workpiece act as parallel currents through two conductors to repel one another. The force of repulsion can be very high, equivalent to surface pressures approximately tens of thousands of pounds per square inch. Thin sheets of material can be accelerated to high velocity in a fraction of a millisecond.

A recent interest in understanding the electromagnetic forming of metals has been stimulated by the desire to use more Al in automobiles. The high workpiece velocities achievable using this forming method enhances the formability of materials such as Al. In addition, the dynamics of contact with the forming die can help reduce, or mitigate, springback, an undesired effect that cannot be avoided in other forming techniques such as stamping. The commercial application of this process has existed since the 1960s. The large majority of applications have involved either the expansion or compression of cylinders (tubes). The forming of sheet materials is more complex and has received little attention.

Approach

The project addresses three main technical areas. The first technical area involves establishing analysis methods for designing forming systems. The methods are based on developed knowledge of forming limits and relations between electrical system characteristics and deformation response for specific Al alloys of interest. The second area of technical challenge is in coil durability. Existing knowledge of electromagnetic forming and relevant knowledge from pulsed-power physics studies are combined with thermo-mechanical analyses, to develop durable coil designs that will be tested experimentally. Until a more thorough understanding is achieved of economic factors determining required durability, a nominal level of 100,000-cycle coil life will be the goal for this project. Finally, the third technical area involves the industrial embodiment of the EMF process. In this project, EMF is expected to be hybridized with conventional sheet-metal stamping. Different approaches to hybridization will be analyzed for issues affecting the economic implementation in a modern stamping plant. Different system concepts will be developed and studied. Existing knowledge of the EMF process and technical achievements in this project will be combined to establish a methodology for designing hybrid-forming systems that can be readily integrated into modern manufacturing facilities for the economic production of automotive sheet-Al compo-

nents. Some of the project focus areas and results are discussed in the following sections.

PNNL EMF System

The EMF system at the Pacific Northwest National Laboratory (PNNL) has been operational since 2001. The system is typically operating at 6,500 V and current levels in excess of 225 kA have been demonstrated. Figure 1 shows a typical response of the EMF system during a 15 kJ discharge of the capacitor bank. The figure shows that the half-current (measuring half the total system current) of the system is approximately 86 kA, so that a total current of 172 kA passed through the load coil within 26 μ s.

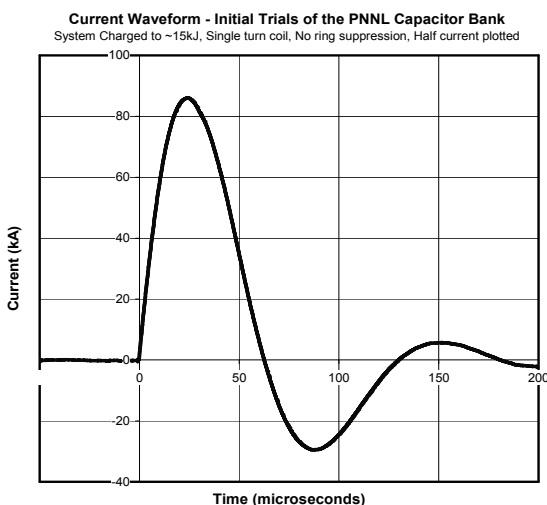


Figure 1. Typical EMF system waveform.

The system has also been cycled several thousands times, at high current levels, while supporting our coil-durability experimental work. The custom-designed control system was also successfully demonstrated in automated, cyclic-loading operating modes. During fiscal year FY 2006, capacitor-bank control system upgrades were completed that result in significantly higher cycle-to-cycle rates. This upgrade increased cycle-to-cycle reliability and improved the efficiency of the data-acquisition system used to sample the electrical response of the entire system, as well as the changing response of the coil assembly.

Coil Design Concepts and Durability

During EMF, the high-intensity electromagnetic forces are applied to the turns of the coil. The coil,

insulators, and support structure must resist these forces, as well as related thermal cycles, without significant permanent deformation or material failure. In contrast to typical cylindrical coils, sheet forming will require coils with general three-dimensional (3D) shapes that are inherently less resistant to forces induced during forming. The key issues involve materials selection and design. Materials must be selected for both electrical conductivity and mechanical properties and they must lend themselves to manufacturing. Materials may also need to be compatible with the presence of coolants and the forces generated during hybrid forming that combines conventional stamping and EMF. The design must integrate these elements while delivering the primary function of a spatial and temporal load distribution that achieves the desired deformations. Coil systems will have to be low-cost, modular, and have high durability (nominally 100,000 cycles) if they are to be relevant to automotive manufacturing.

During the first half of FY 2006, PNNL and Ford initiated the design and fabrication of an automotive-component EMF tool for demonstration of commercial applications. Completion of the tooling is currently expected in the second quarter of FY 2007. This tool will be used to demonstrate commercial applications of EMF, through the demonstration of an EMF re-strike process, for a partially-formed Al component.

During FY 2006, additional coil-durability experiments have focused on increasing the frequency of capacitor discharge to simulate high-repetition rate of automotive manufacturing. With the increasing cycle times, experimental work has focused on development of active cooling approaches for managing the thermal conditions of a rapidly-cycled coil. PNNL fabricated the third-generation, actively-cooled coil design. PNNL evaluated the cooling efficiency of this design under short cycle times at high-energy capacitor-bank discharge. Results from experimental cycling of the coil and thermal measurements were provided as input to the related EMF modeling effort.

The second half of FY 2006 was primarily spent on the validation of an EMF process-simulation tool. This predictive EMF process-simulation tool will allow us to design the process by predicting the EMF field, stress-strain behavior, and the tempera-

ture distribution in the coil. Another focus area was the continued development of the flat-coil design. Improvements were made to both simplify, and thus lower, the cost of the manufacturing of flat coils. Furthermore, the packaging of the flat-coil assembly has been improved for robustness and ease of handling.

Results of Numerical Simulation of EMF Process

The EMF process is challenging to simulate due to the need to model electromagnetic, thermal, and elastic-plastic deformation of materials simultaneously. Many of the commercial research codes have serious limitations and an inability to predict the results of EMF processes accurately. This project originally focused on integrating portions of existing commercial research codes to predict the important characteristics of a 3D electromagnetic-forming process accurately. However, work that is more recent has focused on more accurate, custom process simulations. The current modeling work involves collaboration with Dr. Nick Bessonov in cooperation with the University of Michigan – Dearborn and Dr. Sergey Golovashchenko at Ford.

The objective of numerical simulation was to assist the development of the efficient coil for the restrike operation of preformed Al blank. Preliminary experimental results indicated that sometimes electromagnetic pressure is applied in the area where plastic deformation is not expected. Therefore, we paid specific attention to the distribution of electromagnetic pressure and formation of the blank. Parameters of the discharge were taken from the experimental results produced using a commercial EMF machine and a single-turn coil made of Al-alloy 6061-T6. The maximum energy of the machine was 22.5 kJ with maximum charging voltage of 15 kV. We simulated two cases: Capacitance (C)=0.0002, Faraday (F) and C=0.00025 F. Figure 2 shows the results of the numerical simulation.

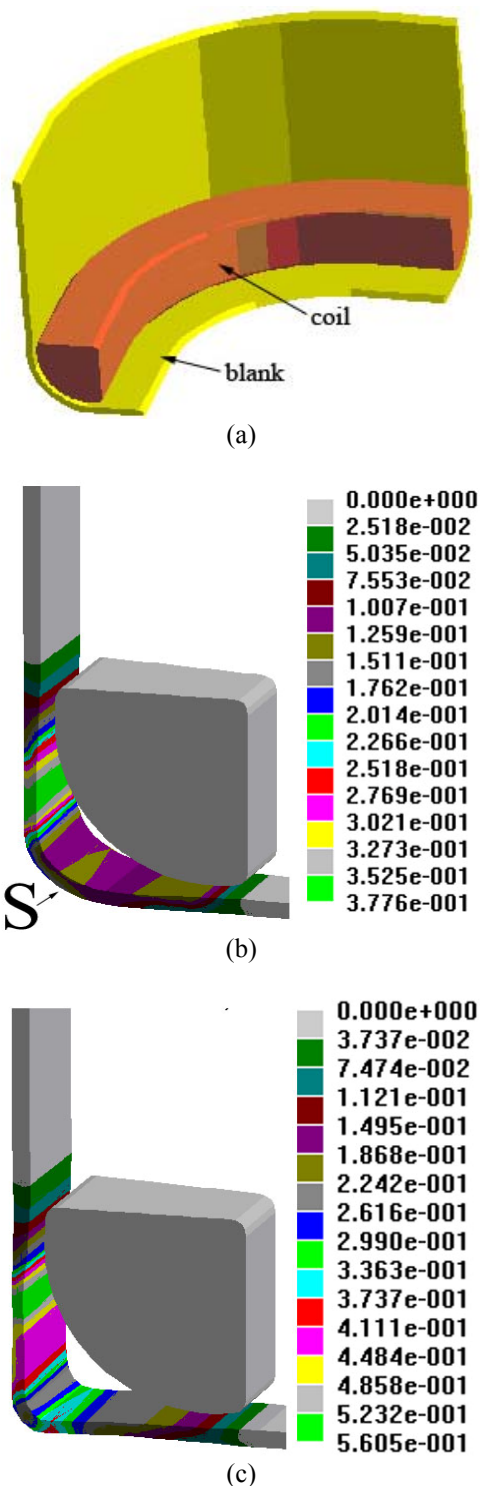


Figure 2. Results of numerical simulation of EMF restrike of 1-mm-thick preformed AA6111-T4 aluminum blank. (a) Initial position of the blank and coil. (b) position of the blank and distribution of plastic strains after the EMF process with the parameters Capacitance (C) =0.0002 Faraday (F) and, Voltage=15 kV. (c) Same as (b) with C=0.00025 F.

Analyzing the strain distribution for two cases, we can conclude that for the case of $C=0.00025$ F, maximum plastic strains were at the formability limit. Displacement of the point S on the external surface of the blank, facing the die and belonging to the bisecting line of the angle formed, is shown in Figure 3.

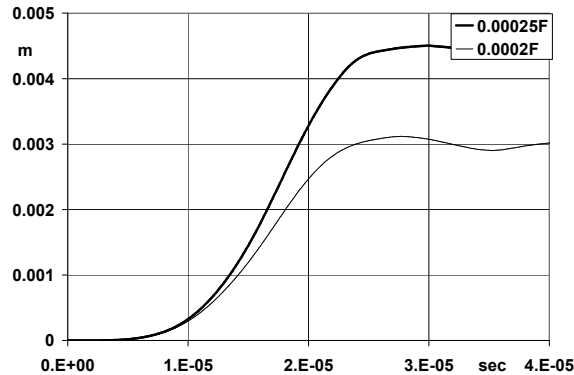


Figure 3. Radial displacements of the point S vs. time for $C=0.0002$ F and $C=0.00025$ F.

As mentioned before, special attention was paid to the distribution of density of electric current and pressure applied to the blank. Figure 4 shows the distributions for the single-turn coil described above.

An attempt was made to simulate a composite coil, which consists of two parts – copper layer facing the blank and the steel layer reinforcing the coil from electromagnetic pressure. As a result (Figure 5), density of electric current in the area of the cross-section facing the blank can be significantly increased. Even though we expect a composite coil to be more expensive due to the necessity of the layers joining, it may provide better efficiency, higher strength and less heat accumulation compared to the coils made of a homogeneous material.

Accumulation of heat in the coil in high-volume EMF process requires special attention. As in well-known induction-heating processes, electric current in EMF processes tends to run within a relatively thin layer, due to the “skin” effect. Later, the heat is redistributed, due to the material thermal conductivity. After every new discharge of the machine, additional heat is generated in the skin layer. This heat generation process can be considered adiabatic. To define the amount of heat, electric current density was integrated over the duration of the process and

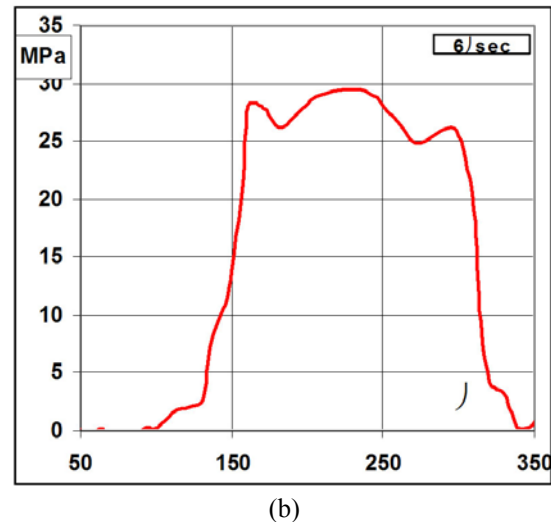
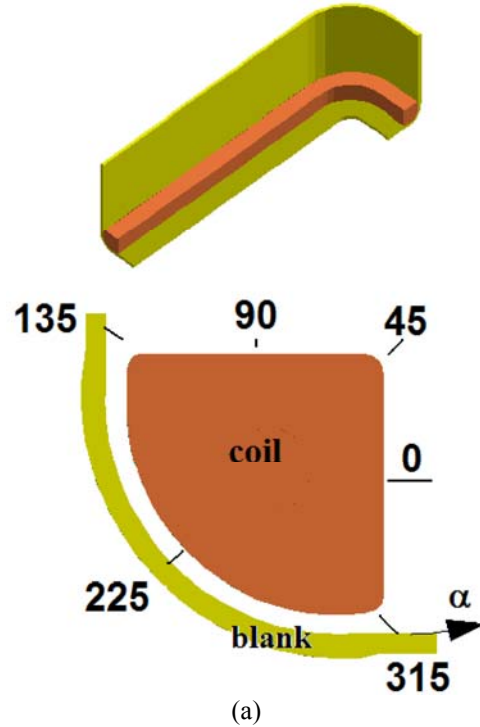


Figure 4. (a) The coordinate system of a cross-section of the coil and (b) the distribution of EMF pressure at time $t=6 \mu\text{sec}$.

produced the distribution of heat due to the active resistance of the coil material (Figure 6). Further heat flow and temperature redistribution happens within a much longer period between pulses of the EMF machine. In production conditions, unloading of the stamped blank and loading of the next blank would take place between two discharges.

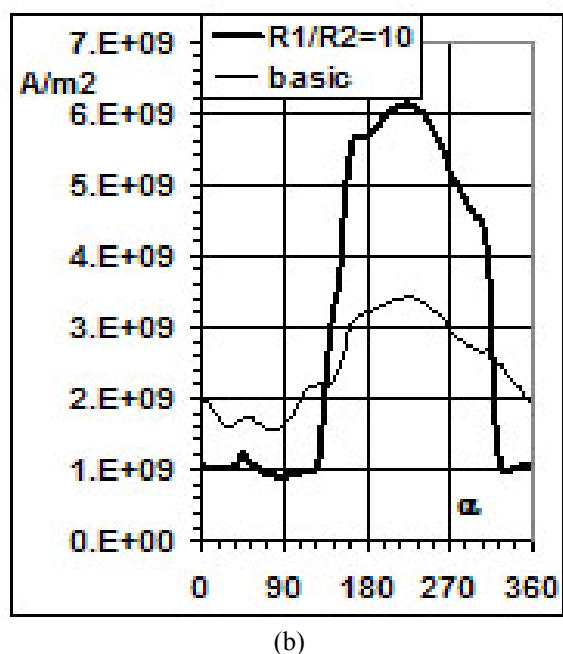
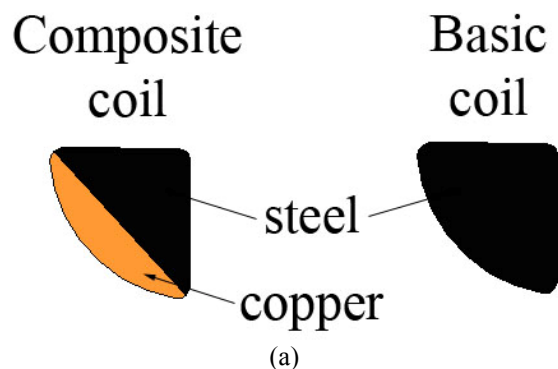


Figure 5. Results of the numerical analysis of the composite (copper-steel) coil compared to the basic steel coil.

In order to develop an efficient cooling system of the coil, a numerical model of the heat transfer through the coil was developed. This model took into account the air-cooling system, which provided the airflow along the coil surface. The parameter, which was expected to drive the cooling process, was the velocity of airflow. According to the results of numerical simulation shown in Figure 7, the airflow with the speed of 20 m/sec could accomplish a satisfactory result, since it provides stabilization of the temperature of the coil. Slower air flows of 15 and 10 m/sec provide stabilization at the higher temperatures, which may not be appropriate for the insulation material and may reduce durability of the coil.

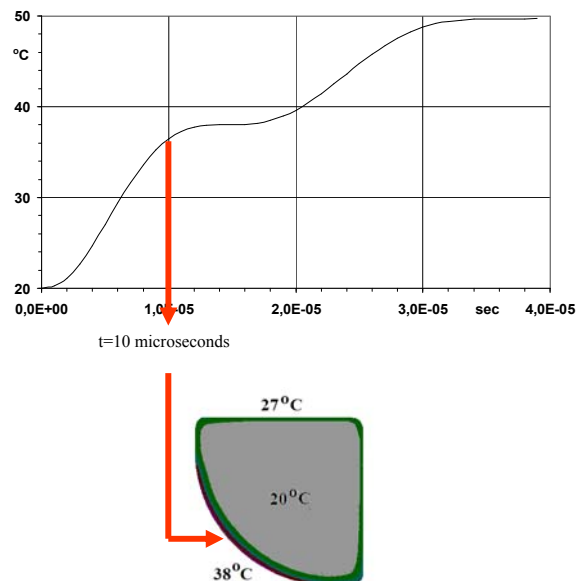


Figure 6. Distribution of maximum temperature vs. time (top) and distribution of temperature in the coil cross-section after 10 microseconds during one discharge of the EMF machine.

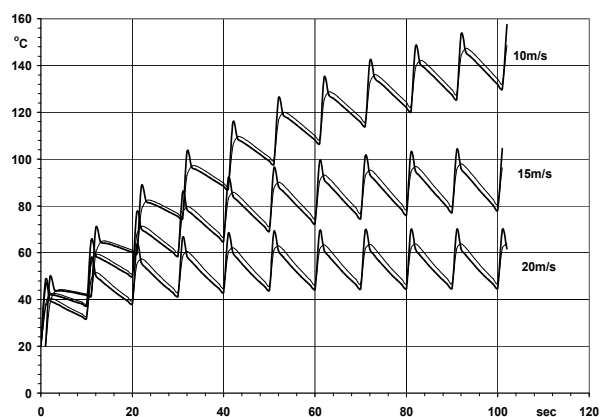
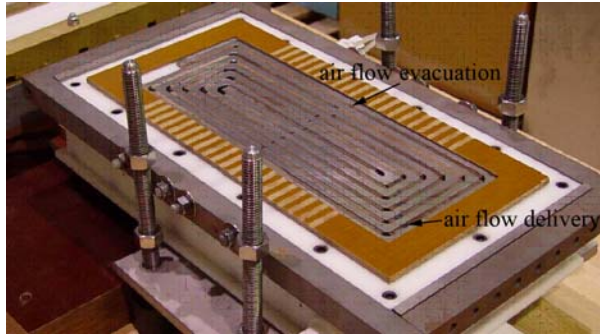
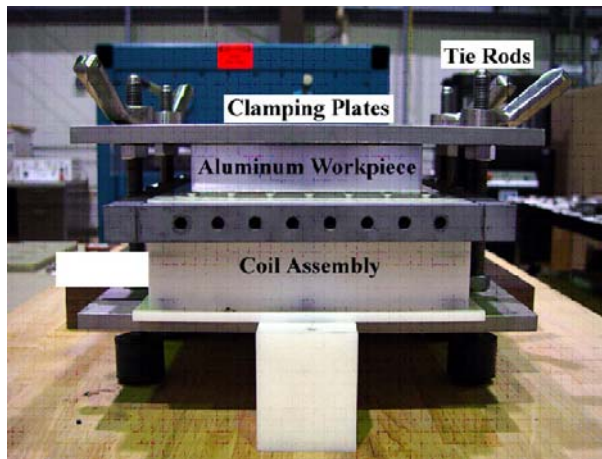


Figure 7. Maximum (thin lines) and average (thick lines) coil temperature vs. time for a production rate of 360 parts/hour with air flow of 10, 15 and 20 m/sec.

Experimental study of the cooling process was conducted using the flat coil made of steel and micarta insulation plates, illustrated in Figure 8. Airflow was delivered through the slots between the micarta plates in the corners of the coil. The spiral surface was insulated from the blank by a thin plate of insulation material. The airflow was directed between the spiral surface and insulation plate, so it would provide cooling of the working surface of the coil where maximum amount of heat is generated.



(a)



(b)

Figure 8. Experimental fixture employed for experimental study of coil durability and heat accumulation. (a) Flat coil with air-cooling system. (b) Assembled fixture ready for testing.

Conclusions

This work has developed numerical models that describe three critical elements of the EMF process: 1) propagation of the electromagnetic field through the coil-blank system and generation of pulsed electromagnetic pressure in specified areas, 2) high-rate deformation of the blank and, 3) heat accumulation and transfer through the coil with an air-cooling system. The process models provide capability to analyze EMF restrike processes from the perspective of coil design, blank deformation, and cooling systems for the coil.

E. Aluminum Automotive Closure-Panel Corrosion Test Program (AMD 309ⁱ)

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Contractor: U.S. Automotive Materials Partnership

Contract No.: FC26-020R22910

Objective

- Develop a standardized cosmetic corrosion test for finished aluminum (Al) automotive body panels that provides a good correlation with in-service testing and field performance.

Approach

- Conduct laboratory testing, outdoor exposures, test-track exposures and in-service testing.
- Evaluate test data to determine which accelerated tests correlate with in-service testing.
- Conduct iterative laboratory testing to improve correlation between lab tests and on-vehicle exposures.

Accomplishments

- Initial laboratory tests, test-track exposures and outdoor exposures completed
- On-vehicle tests have been exposed for three years out of five planned.
- Corrosion product analyses conducted for some laboratory tests and for two-year exposures on-vehicles.
- Round-robin testing conducted for the three lab tests down-selected from initial lab tests.
- Conducted an initial evaluation of three existing ASTM tests with sulfur in the exposure.

Future Direction

- Modifications of the more promising accelerated laboratory tests are now being considered in an effort to find a lab test with improved correlation to on-vehicle exposure results in terms of the extent and morphology of the corrosion as well as the composition of the corrosion products. On-vehicle exposures will continue until the panels have been exposed on vehicles for five years.
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Introduction

Although Al closure panels have been used on numerous vehicles for several years, the degree of confidence in predicting service performance has not been high due to the lack of an accelerated corrosion test that mimics field performance. Automotive manufacturers and their suppliers often rely on accelerated corrosion tests that were developed for evaluating steel, but these tests are not always consistent with in-service Al closure-panel performance.

In order to address the need for an accelerated Al corrosion test, a group comprised of representatives from the US automotive manufacturers, Al suppliers, coating suppliers, and other associated suppliers was formed in 2000. The goal of this group has been to identify and implement a standardized, accelerated corrosion test for cosmetic corrosion of Al that exhibits the same appearance, severity, and corrosion products that are exhibited on in-service Al components.

Experimental

Materials

In 2001, the first step in the development of a new cosmetic corrosion test occurred with the establishment of a reservoir of painted panels. These panels would then be used in the subsequent evaluation of all test methods. As listed in Table 1, the substrate materials, metal finish and paint processing variables were selected to give a range of cosmetic corrosion performance. Several Al alloys used in the United States and in Europe, both current and historical, were included. Electro-zinc-coated steel and uncoated cold-rolled steel were included as reference materials. Two Al alloys were processed to simulate metal finishing in an automotive assembly plant body shop. Two sizes of panels, 2" x 4" and 4" x 6", of each of the materials were painted with a typical automotive paint system. This paint system included zinc-phosphate pretreatment, medium-build cathodic electrophoretic priming (E-coat), and spray painting with a primer surfacer and white basecoat/clear topcoat system for a total paint film thickness of approximately 100µm. One set of 6111 panels (Panel Code B) was processed through the phosphate pre-treatment with lower fluoride concentration (comparable to the fluoride

level used for steel-only vehicles which results in lower phosphate coating weight). Also, since qualification testing is often done on panels that are processed only through the electrophoretic primer (E-coat) step, another set of 6111 panels (Panel Code C) was processed only through the E-coat step (i.e., standard fluoride for Al but no basecoat or clear-coat applied). Panel code C was evaluated in accelerated tests only (no on-vehicle or proving ground exposures).

Table 1. Materials.

Panel Code	Alloy Substrate	Metal Finish	Paint System
A or 1	AA6111-T4PD	Mill	Standard
B or 2	AA6111-T4PD	Mill	Low F-
C or 3	AA6111-T4PD	Mill	Ecoat Only
D or 4	AA6111-T4PD	Sanded	Standard
E or 5	AA6016-T4	Mill	Standard
F or 6	AA6022-T43	Mill	Standard
G or 7	AA2036-T4	Sanded	Standard
H or 8	EG 60 Steel	Mill	Standard
I or 9	Cold Rolled Steel	Mill	Standard

Panels were prepared as-needed for testing with two parallel scribes penetrating through the coatings to the substrate. The panels were provided to the testing laboratories as fully-prepared painted and scribed panels. Triplicate sets of the painted and scribed samples have been exposed in a variety of environments, including laboratory, static outdoor exposure, proving-ground, and on-vehicle tests.

Evaluation Method

For this study, an optical imaging system developed by Atlas Material Testing Technology LLC was employed to quantitatively interpret the degree of cosmetic corrosion. The imaging system employs controlled illumination conditions, high-resolution digital-image capture and advanced algorithm-based image- and data- analysis methodologies. [1].

Four geometrical attributes of the cosmetic corrosion were measured: area of corrosion, maximum length, minimum length and average length. The area of corrosion was found to be the most representative and comprehensive measurement. Because the size of the panels and therefore the scribe lengths for the lab tests were different from the other tests, the corrosion area was normalized to the length of the scribe (i.e., area per length). The normalized

corrosion areas for triplicate panels (2 scribes per panel) were then averaged and the results are reported as “normalized average area”.

Laboratory Tests

In the initial round of testing, each of the tests listed in Table 2 was conducted at two laboratories as a limited check on the lab-to-lab reproducibility of the initial results. After comparing the initial round of test results to preliminary on-vehicle exposure results, three of these tests (Ford Arizona Proving Grounds Exposure (APGE) [2], ASTM G85 - Annex 2 [3], and HCl Dip [4]) were selected for further evaluation.

Round-robin evaluations of these test methods have been conducted. The duration of the tests was varied in an attempt to further improve the correlation of these accelerated tests with the results from the on-vehicle exposures. Each test was conducted at four to five laboratories to more thoroughly evaluate the repeatability and reproducibility of the test methods. Three additional tests were added in the second round of testing to include exposure to sulfur. They were ASTM G85 Annex 4 [5] ASTM G85 Annex 5 [6] and ASTM G87 [7]. A listing of the accelerated laboratory tests that were run in the second round of testing is given in Table 3.

Table 2. Laboratory Test Evaluated in Initial Round of Testing.

Test Procedure	Exposure (s)
SAE J2334	40, 60 & 80 cycles
GM 9540B	40, 80 cycles
Ford APGE	35 & 70 cycles
ASTM D2803 (50,80 & 100% RH)	6 weeks
ASTM G85 Annex 2	3 weeks
VDA 621-415	10 cycles / 70 days
ASTM B117	500 & 1000 hours
CCT IV	70 cycles
HCl Dip	8 weeks
KWT	6 weeks

Table 3. Laboratory Test Evaluated in Second Round of Testing.

Test Procedure	Exposure (s)
Ford APGE (Manual & Automated Humidity Cycle)	70 cycles
ASTM G85 Annex 2	1 & 2 weeks
HCl Dip	3 & 6 weeks
ASTM G87	20 cycles
ASTM G85 Annex 4	500 hours
ASTM G85 Annex 5	500 hours

On-Vehicle (In-Service) Exposures

It is critical when developing a laboratory-based test that test-to-field correlation be performed. In an effort to capture real-world data in developing this test, it is necessary to expose these panels to severely corrosive environments that represent “worst case” real-world service environments. Suitable environments exist in the northeastern United States, southeastern coastal areas of the United States, and southeastern Canada. The five sites selected for this study were: 1) Detroit, Michigan; 2) Florida; 3) St. Johns, Newfoundland; 4) Montreal, Quebec; and 5) an Ohio-to-New York truck route.

Two sets of 2” x 4” test panels are exposed on each vehicle (two vehicles per site). Each set of 24 panels (three replicate samples of each of the eight material variations) are attached to a mounting panel (16” x 12”) using double-backed tape prior to mounting on the vehicle. At the Detroit, St. Johns, and Montreal sites, one set is mounted on the hood of each vehicle (horizontal orientation) and one set on the right front door of each vehicle (vertical orientation). At the Florida and Ohio-New York sites, the panels are mounted beneath the trailer frame behind the front wheels (vertical orientation only). Each panel contains 2 diagonal scribe lines which are 2” long and 1” apart. The panels will be exposed for a total of five years of in-service exposure. Intermediate evaluations will be conducted when possible.

OEM Test-Track Exposure

Completed OEM test-track results were published previously [8] and are not repeated in this report.

Outdoor Exposure

Completed outdoor exposure test results were published previously [8] and are not repeated in this report.

Corrosion-Product Analysis

The corrosion products from selected on-vehicle exposure panels have been analyzed using a variety of electron-optical techniques. Select panels were removed from the on-vehicle exposures at three locations (St. Johns, Montreal, and Detroit) after two years of exposure for compositional analyses of the corrosion products.

Top-down analysis of the corrosion products was carried out after stripping the surrounding paint layer in 1-methyl-2-pyrrolidone solvent. Water was not used during the stripping procedure so as to preserve any chloride/sodium species present within the corrosion product. The panels were examined using a Leo 440 scanning electron microscope (SEM) equipped with a Quartz XOne energy dispersive X-ray (EDX) analysis system. SEM/EDX technique was chosen for this examination because the amount of corrosion product on Al closure panels is very small, making more traditional analytical procedures impractical. In addition, the use of SEM/EDX allows not only for a measurement of the chemical species present, but also for an analysis of the distribution of these species in and around the corroded area on the panel.

Results and Discussion

Lab-Test and On-Vehicle Results

At this point in the program a limited amount of service-relevant results from the on-vehicle exposures is available. Although there is significant variability both from panel-to-replicate-panel and from vehicle-to-vehicle for a particular exposure site, the most consistent result is that panels D, G, and I exhibited more corrosion than the other substrates as is illustrated by the images in Figure 1 of a set of panels from the Detroit on-vehicle exposures after being exposed for approximately eighteen months.

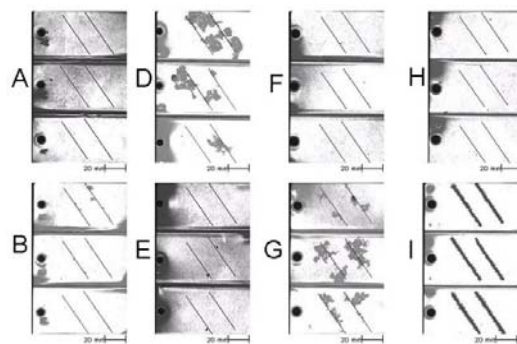


Figure 1. Detroit On-Vehicle Test with 1.5 Years Exposure.

From the preliminary on-vehicle results it is apparent that the panels with metal finishing (D & G) generally have more corrosion than the other Al substrates and that the cold-rolled steel (I) has more corrosion than the electro-galvanized steel (H). The normalized average area from on-vehicle service relevant exposures in Detroit and Montreal are plotted in Figure 2. Based on these preliminary on-vehicle results, accelerated tests that also show a significant difference between the substrates with metal finishing (i.e., sanding) and those without metal finishing would appear to correlate better with the preliminary observations from on-vehicle testing. Many of the accelerated lab tests in the initial round of tests did not show a significant difference between the substrates with and without metal finishing. Of the initial set of laboratory test methods evaluated in the program, only the APGE (one lab only), ASTM G85-A2 test and HCl dip tests appeared to show a significant difference in corrosion performance between the substrates with metal finishing (i.e., sanding) and those without metal finishing.

Because these three accelerated tests had shown signs of possible correlation with on-vehicle exposures, they were selected for further evaluation. In an attempt to improve the correlation of the type and extent of corrosion, reduced durations of the HCl Dip (three- and six-week) and ASTM G85-A2 (one- and two-week) exposures were evaluated. The tests were also conducted as round-robins with a minimum of four laboratories to further evaluate the reproducibility of the tests. Also, in order to determine if the divergent results from the APGE

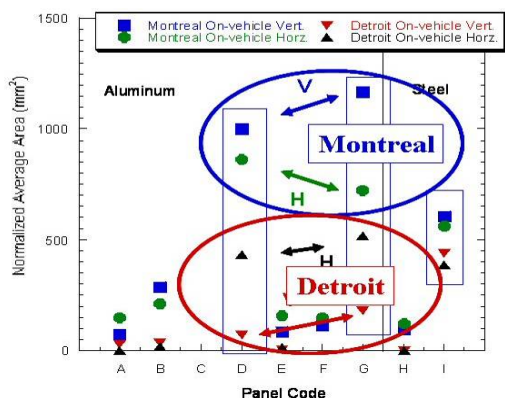


Figure 2. Normalized average area: Detroit and Montreal with two years exposure.

tests were associated with means of cycling (i.e., automated vs. manual), the 70-cycle APGE test was repeated at six laboratories, three with manual cycling and three with automated cycling.

In Figures 3 and 4 the results from the ASTM G85-A2 round-robin are shown with the results from the worst-case on-vehicle exposure results to date, Montreal vehicle #2.

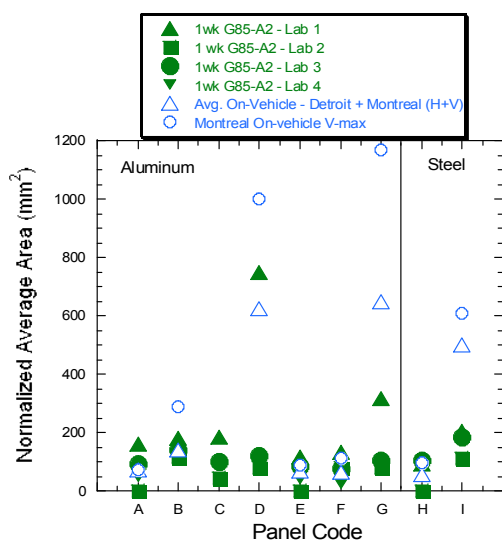


Figure 3. ASTM G85-A2 round-robin tests – 1-week with results from the worst-case on-vehicle (Montreal).

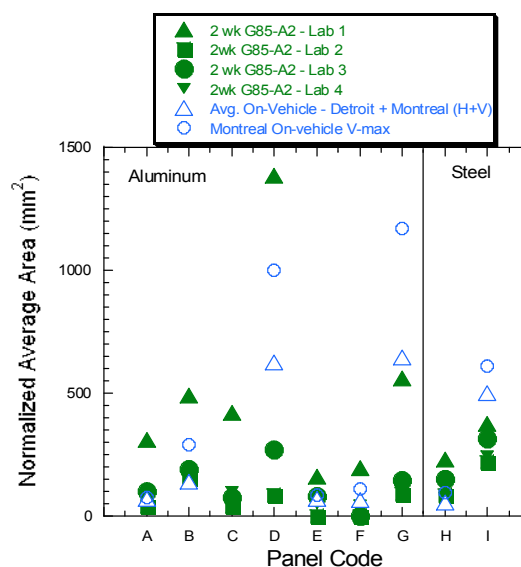


Figure 4. ASTM G85-A2 round-robin tests – 2-weeks with results from the worst-case on-vehicle (Montreal).

The relative ranking of the panels in the two-year Montreal on-vehicle were slightly different for the panels exposed vertically on the doors and those mounted horizontally on the hoods:

- Vertical = G>D>>I>B>rest
- Horizontal = D>G>I>>B>rest

The ASTM G85-A2 results for Lab #1 were similar to the previous results in the initial round of testing but significantly different from other labs in the round-robin. The relative ranking of the panels in ASTM G85-A2 is as follows: Lab #1 is reasonably similar to that from the Montreal vehicle:

- 1 week – Lab #1 = D>G>rest
(Other labs no differentiation)
- 2 weeks – Lab #1 = D>>G, B, C, A>rest
(Other labs little to no differentiation)

For Lab #1, the relative ranking of the Al substrates is reasonably similar to that from the Montreal vehicle as was noted in the initial tests. The lack of differentiation for the other three labs is an indication that the actual test conditions were substantially different. After these results came to light, we reviewed the actual conditions at each lab. A detailed scrutiny of the test specification revealed parts of the test description could be readily misinterpreted and that the actual chamber

conditions are very specific and may not be able to be run on all standard corrosion equipment.

Figures 5 and 6 show the results of the HCl dip test round-robin with the results of Montreal in-service vehicle #2. The HCl dip test was run for two exposure time periods (3 weeks and 6 weeks) at four laboratories. Overall, the 3-week exposure does not show as much corrosion as seen in the field. Therefore, it is unlikely that the 3-week test is long enough to characterize in-service corrosion performance.

For the 6-week HCl dip test, the corrosion performance on substrates D and I is much closer to that seen in the on-vehicle exposures. However, two of the laboratories (lab #2 and lab #4) significantly over-predict the corrosion on substrates A, B, and H compared to the 2-year in-service performance. This over-prediction occurs only at two of the four laboratories.

The other two laboratories (lab #1 and lab #3) follow the corrosion trends seen in the on-vehicle exposures, with the only exception being for substrate G. Further investigation is needed to understand the test conditions at the laboratories running the HCl dip test to explain the differences in the results after six weeks of testing.

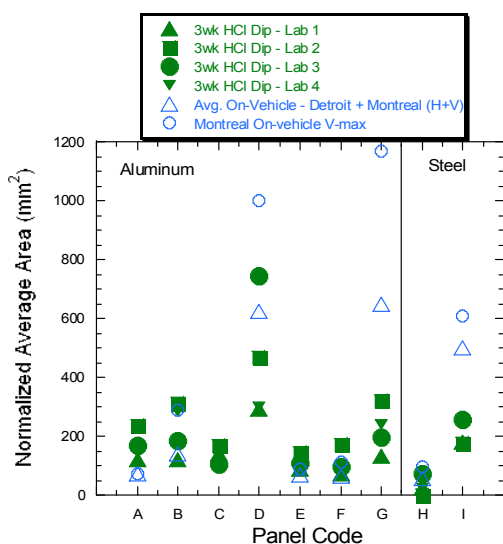


Figure 5. HCl dip round-robin tests – Three-weeks with results from the worst-case on-vehicle (Montreal).

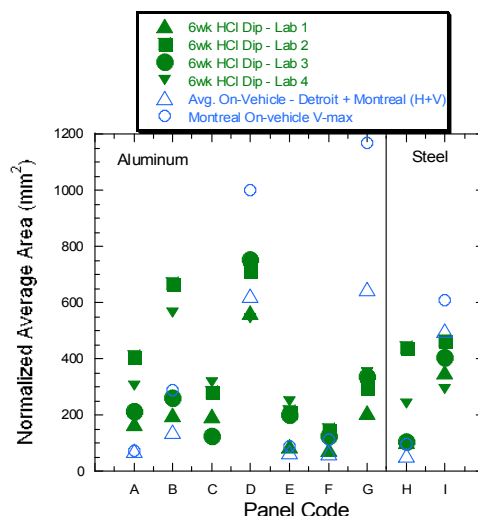


Figure 6. HCl dip round-robin tests – Six-weeks with results from the worst-case on-vehicle (Montreal).

For the second round of APGE (70 cycles), tests were conducted at a total of six labs, three with manual cycling and three with automated cycling. The results from four of the six labs are available at this time and are shown in Figure 7. The results from one test lab at which the cycling was conducted manually appears to differentiate between substrates D, G, and I and the remaining substrates thereby showing reasonable correlation to the on-vehicle exposures but the other three labs do not show this differentiation.

In the first round of tests, only the lab that had run the test with automated cycling seemed to differentiate the substrate groups. At that time, the lack of lab-to-lab reproducibility for the APGE test was suspected to be related to differences between manual and automatic cycling, but these more recent results contradict the earlier results and indicate that there are other, less obvious, sources for the lab-to-lab variability in the results. Further investigations will be carried out to understand the test conditions at the laboratories running the APGE test to explain the differences in the results.

The limited results from the two sulfur bearing tests are shown in Figures 8 and 9. To date, these tests have only been run at one lab each. The results for the salt/SO₂ fog test (ASTM G85-A4) show significant corrosion on most of the panels.

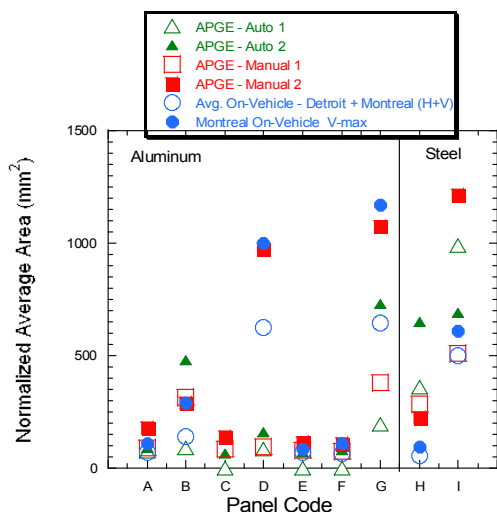


Figure 7. Ford APGE round-robin tests – 70 Cycles with results from the worst-case on-vehicle (Montreal).

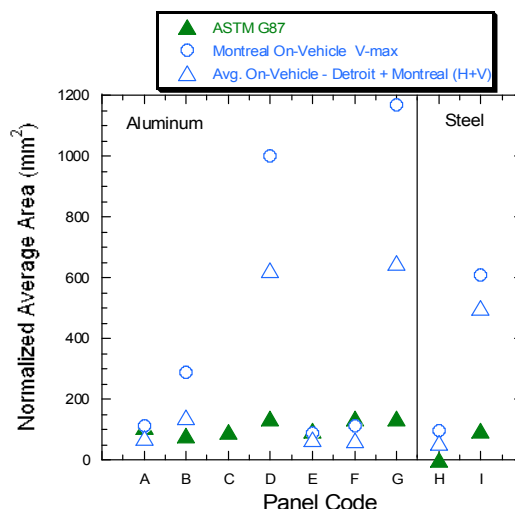


Figure 9. ASTM G87 round-robin tests – 500 hours with results from the worst-case on-vehicle (Montreal).

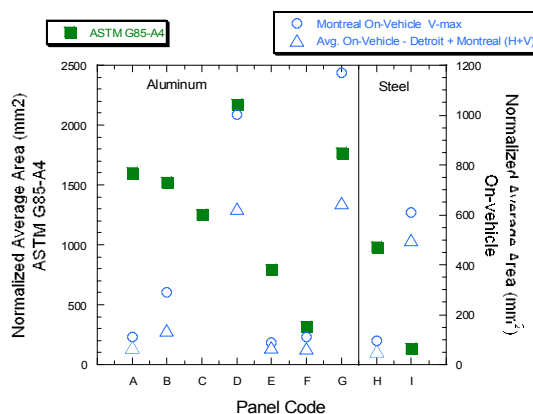


Figure 8. ASTM G85-A4 round-robin tests – 500 hours with results from the worst-case on-vehicle (Montreal).

Although the D and G substrates have the most corrosion, this test method as conducted does not appropriately differentiate D and G from the other substrates (A, B, E) which have far less corrosion in the on-vehicle exposures than was observed in the ASTM G85-A4 test. This test method also appears to be more severe for galvanized steel than for cold-rolled steel which is opposite of the on-vehicle exposures as illustrated in Figure 8.

The lone set of results for the moist SO₂ test (ASTMG87) illustrated in Figure 9 shows very little corrosion on any of the substrates and does not appear to have differentiated the substrate groups in the manner observed in the on-vehicle tests.

Corrosion-Product Analysis Results

Table 4 presents a description of Al panels examined in this study. These panels came from three different in-service exposures (St. Johns, Detroit and Montreal). SEM/EDX was performed at several areas on each panel. Only selected, but representative, results from this investigation are presented here. EDX spot analysis was performed at several locations to determine the variations in the corrosion-product composition from location to location.

Table 5 presents the EDX spot analysis results from various locations within the corroded region for representative panels from the St. John's exposure. Sulfur was detected on all three Al panels, whereas chlorides were detected on panels A and G only. Moreover, the tip of the filiform filament (spots SA1, SG2 etc.) exhibited much greater concentrations of chlorides species. In general, the average sulfur values, calculated from ten to fifteen spot analyses on each panel, were greater than the average chloride values for the Al panels.

Table 6 presents the results from panels A and D exposed in Montreal. The results from the spot analysis indicate that chloride-rich areas were detected in the corroded region as well as in the scribed region. In contrast, sulfur-rich areas were not observed on panel A and only at the scribed region on panel D.

Table 4. Description of Panels Selected for Corrosion Product Analysis.

Location	Panel Code	Panel Description
St. John's, Newfoundland	A	Vehicle 3 rep 1H top hood 3
	D	Vehicle 3 rep 3H bottom hood 2
	G	Rep 1 H top hood 3
	I	Ford-061 Vertical
Detroit, Michigan	A	Ford-061 Horizontal
	B	Ford-061 Horizontal
	D	Ford-061 Horizontal
	D	Ford-061 Vertical
	I	Ford-061 Horizontal
	I	Ford-061 Vertical
Montreal, Quebec	A	Field Motor Vehicle 2
	D	Vehicle 3 rep 1H top hood 3

Table 5. Composition of Corrosion Products on Panels from St. John's Exposure (weight %).

Spot	O	Al	P	S	Cl	Ca	Zn
SA1	56.3	33.2	2.7	3.2			1.3
SA2	61.5	31.5	0.7	2.3	2.6		0.9
SA3	9.7	8.0	2.7	0.4	0.1		6.1
SA4	58.2	30.4	1.0	0.8	0.5		7.6
SA5	25.6	69.7	1.2	1.0	0.1	0.3	1.6
SD1	60.4	31.0	2.2	3.0		0.2	2.7
SD2	60.1	29.8	3.1	2.6		0.2	4.2
SD3	46.2	37.8		1.2			
SA9	40.6	31.3	7.9				15.5
SG1	46.5	27.0	6.8		2.4		3.2
SG2	58.6	29.1	3.2	0.1	0.4		1.3
SG3	47.1	20.8	8.7		2.3		3.6
SI1	7.1						91.4
SI2	31.6		0.1	0.2		0.3	52.2
SI3	26.4	0.7			0.3	4.2	6.0

EDX spot analyses were performed at ten different locations on panel A and sixteen different locations on panel D, though the data from only three to four locations are presented in Table 6. The trends from these extensive EDX spot analyses indicated that the Montreal exposures exhibited more chloride-rich regions than the sulfur-rich areas. This observation is in contrary to the data from St. John's panels.

Table 6. Composition of Corrosion Products on Panels from Montreal Exposure (weight %).

Spot	O	Na	Al	P	Cl	Ca	Zn
MA1	54.3	4.6	34.6	1.2	1.5	3.1	0.1
MA2	49.4	1.6	30.2	10.1	2.5		
MA3	48.3	3.1	30.1	4.9	1.0	4.1	6.3
MA4	34.0		13.1	11.4			35.2
MD1	54.4	2.9	29.9	5.7		7.0	
MD2	63.4	1.0	33.3	1.1		0.7	
MD3	46.8	1.6	26.5	5.8		2.5	13.7

Table 7. Composition of Corrosion Products on Panels from Detroit Exposure (weight %).

Spot	O	Al	P	S	Cl	Zn	Fe
DA1	59.6	28.5	1.7	3.8	3.5	2.4	
DA2	54.9	33.1	1.9	4.6	0.2	2.8	
DB1	58.4	39.1	0.3	1.1	1.0		
DB2	55.4	40.9	0.2	1.7	1.5		
DDH1	57.3	32.0	3.9	1.5		4.3	
DDH2	6	31.9	2.4	1.9	0.2	3.0	
DDV1	61.8	27.7	1.0	4.0	0.9		
DDV2	35.6	61.6	1.2				
DIH1	24.7				3.5		71.3
DIH2	34.4				0.4		64.6
DIV1	40.4			0.4	2.3		55.3
DIV2	43.5				0.5		56.0

Finally, EDX spot analysis data from the Detroit exposures are summarized in Table 7. The data from panel A indicate that the corroded region was enriched with sulfur. Chloride concentrations were also detected at the tip of the filiform filament. EDX spot analysis data (Table 7) also shows that all the spots exhibited sulfur or chloride or both. Sulfur and chloride enrichment was also observed on panel B. EDX elemental distribution maps for horizontal and vertical D panels indicate that the horizontal panel exhibited sulfur within the corrosion product, while both sulfur and chlorides were detected at the corroded region of the vertical panels. However, the EDX spot analysis data shown in Table 7 indicate that small amounts of chlorides could be detected within the corroded region of the horizontal panel.

Conclusions

Correlation of the accelerated corrosion tests to on-vehicle corrosion performance is the primary goal of this test development effort. From the preliminary on-vehicle results it is apparent that the panels with metal finishing (D & G) generally exhibit more corrosion than the other Al substrates. In the first round of accelerated corrosion testing, only three test methods (APGE, HCl Dip, and ASTM G85-A2) were able to distinguish substrates D and G from the other Al test samples. However, the corrosion morphology on those substrates did not appear to be the same as that found on the on-vehicle panels.

In the corrosion product analyses of the on-vehicle panels, both sulfur and chloride were detected to varying degrees. Overall, the Al panels appeared to exhibit greater amounts of sulfur species within the corrosion products than the steel panels that were exposed to the same environment. This would seem to indicate that the Al panels were more sensitive to the presence of sulfur and that sulfur plays a more significant role in the corrosion of Al than in the corrosion of steel. As the first round of accelerated testing did not include a test that incorporated an exposure to sulfur, a second round of testing was run that included tests with sulfur species in the exposure (ASTM G87, ASTM G85-A4, and ASTM G85-A5).

The results of ASTM G87 showed very little corrosion on the Al panels. As this test provided exposure to moist SO₂ and no exposure to chloride, it would seem to indicate that either corrosion on Al does not occur with exposure to SO₂ alone or that another sulfur species may be responsible for corrosion on Al.

ASTM G85-A4 is a salt/SO₂ fog test. Al panels that underwent ASTM G85-A4 exhibited significant corrosion on many of the panels. Although the test looks promising for the prediction of corrosion on substrates D & G, it significantly over-predicts the corrosion on substrates A and B when compared to the on-vehicle panel exposures. Further evaluation of this test is needed to determine if the balance of salt and SO₂ or other test parameters can be optimized to provide a better correlation to field performance for all of the Al substrates being tested.

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Presentations/Publications/Patents

SAE 2002B-203
 SAE 2003-01-1235
 SAE 2005-01-0542
 SAE 2006 Oral Only

ⁱ Denotes project 309 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.

F. Improved Automotive Suspension Components Cast with B206 Alloy (AMD 405ⁱ)

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Contractor: U.S. Automotive Materials Partnership

Contract No.: FC26-02OR22910

Objective

To establish the commercial viability of B206 alloy for suspension components, by providing needed fundamental information on this alloy system; and by overcoming technical issues that limit the light weighting applications of this alloy. Once the important technical issues are solved, we should be able to provide mechanical properties equivalent to forged aluminum suspension components in net-shaped B206 alloy castings. This would allow us to lightweight automobiles and trucks in a cost-effective manner.

Approach

Four major technical focus points have been identified for this project. Accordingly, the work will be conducted in four separate phases:

1. Determine the effect of alloy composition on mechanical properties in the T4 and T7 heat-treated conditions and establish the feasibility of using less expensive versions of the alloy.
2. Study heat treatment of B206 alloy and establish combinations of aging time and temperatures which produce desirable stress-corrosion immunity. This portion of work will also determine the feasibility of using improved T7 heat treatment cycles, to increase elongation in this temper.
3. Create cost models for automotive suspension components produced by different processes and different materials.
4. Produce control-arm castings using two different casting processes. Test components produced in the T4 and T7 tempers to provide required engineering information and establish the feasibility of using cast B206 alloy components to replaced forged aluminum parts.

Accomplishments

Kick-off meetings officially began this project early in October, 2005. All purchase orders were in place in February, 2005. Dr. Geoffrey Sigworth handed over the administration of the project to Dr. Murat Tiryakioğlu in March 2006. Phases 1, 2 and 3 are completed. Casting production is about to start at Nemak as of December 9, 2006. Phase 4 is expected to be finished by March 2007.

¹ Dr. Tiryakioğlu took over administrative responsibilities of this project from Dr. Geoffrey Sigworth in March 2006.

The **phase 1** work is complete. A study of tensile properties versus alloy composition was conducted by researchers at Alcan International. These results show that best results are obtained with two separate alloy compositions, depending on whether the T7 or the T4 temper is used. These two alloy compositions are (in wt.%):

1. T4 Temper

The alloy contains 4.7 to 4.9% Cu, 0.35 % Mg and 0.2 % Mn. The expected tensile properties are (YS, UTS, elongation): 250-260 MPa, 430-450 MPa, and 18-22%.

2. T7 Temper

For a ductile T7 version, the alloy contains 4.2 to 4.4% Cu, 0.15% Mg, 0.2% Mn, 0.10%Fe, 0.10%Si. The expected average tensile properties would be (YS, UTS, elongation): 370-390 MPa, 445-455 MPa, and ~9% elongation.

In addition to the above results, a set of casting guidelines has been prepared for foundrymen who want to pour B206 alloy.

A second stage of phase 1 casting trials was completed in September, 2005 by Nemak researchers at their Central Development and Technology Center near Monterrey, Mexico. Several different alloy compositions were prepared and 'wedge' castings were made. The 'wedge' castings were poured to establish the tensile properties of the alloy as the solidification rate varied from 30 seconds to 30 minutes. In addition, hot-crack-test castings were poured to determine the effect of alloy composition on castability.

Phase 2 was conducted at the University of Windsor under the direction of Prof. Jerry Sokolowski. Alcan International also assisted this phase of the project by providing additional testing. A survey study of the aging of B206 alloy was completed. Samples were aged at temperatures between 125 and 225°C for times ranging from two to forty-eight hours. The hardness and electrical conductivity were measured, and the samples were subjected to a corrosive medium to establish their vulnerability to intergranular attack. A report of these experiments was issued in October, 2005. Additional studies were conducted to establish the kinetics of the solution-heat-treatment process. Attempts to develop an alternative T7 aging process to increase elongation in that temper were mostly unsuccessful. More work is needed.

Phase 3 has been completed. A cost model was developed by Edmund A. Herman, P.E. of Creative Concepts Company, Inc. in March 2006. A Microsoft Excel spreadsheet was developed which can be used to compare costs of producing castings using A356-T6, B206-T4 and B206-T7 alloys.

Phase 4 is in progress. The design work needed for this phase was initially completed at Hayes Lemmerz. In April 2006, there were intense discussions on how the filling system should be designed to minimize the entrainment of surface oxide films and therefore maximize mechanical properties. Dr. Tiryakioğlu and Prof. John Campbell provided Mr. Greg Woycik at Hayes Lemmerz with a conceptual design of a filling system that was expected to minimize the damage to liquid metal during mold filling. However, Mr. Woycik was unexpectedly released of his job at Hayes Lemmerz. Hayes Lemmerz is no longer involved with this project. The gating system design concepts proposed by Tiryakioğlu and Campbell were adopted by Nemak and final gating system design was developed with the assistance of Prof. Campbell. Mold-filling simulations using Magma software showed significant improvement over previous designs.

Future Directions

Castings to be produced at Nemak will be tested at Westmoreland Mechanical Testing and Research and General Motors Corporation. These tests include component fatigue, tensile, fracture toughness, compressive testing and corrosion. In addition, deformation characteristics will be evaluated to determine whether any outliers in tensile tests are due to structural defects that can be avoided with better melt quality and modifications to mold filling system design. A full project report will be available in April 2007.

Introduction

206 alloy is significantly stronger than 356 alloy, and has mechanical properties approaching some grades of ductile iron. It also has excellent high temperature tensile and low-cycle fatigue strength. Consequently, this material could be used in a number of applications to reduce vehicle weight. Cost savings may also result, because less material would be required to provide the strength needed for the application. In spite of its excellent properties, however, 206 alloy is seldom used because of its propensity for hot cracking. GKS Engineering has discovered a better method to grain refine this alloy, which reduces the tendency for hot cracking. This material has a number of potential applications, but its high strength and excellent ductility make it an ideal candidate for suspension components. Consequently, in the first stage of work (Project AMD 305ⁱⁱ -- completed in May, 2002) control arms were produced via a tilt-pour/permanent mold casting process to establish the viability of this material for these safety critical components.

The work completed under AMD 305 showed that extremely high mechanical properties can be obtained. The tensile properties of permanent-mold B206 alloy control arms were nearly the same as (or slightly better than) those found with many forged aluminum components, and the low-cycle fatigue life of B206 alloy is ten times that of A356 alloy castings for an equivalent stress level. AMD 305 also showed that the permanent-mold casting process, although suitable, may not be the best manufacturing process for 206 alloy. Traditional sand casting and composite casting methods (such as Nemak's semi-permanent mold precision sand casting process) are more forgiving of hot cracking. The additional work proposed in this project will examine the technical feasibility of producing B206 alloy suspension components in three other casting processes. Other important technical and commercial issues related to B206 will also be addressed. The object is to provide the technical and economic data needed to justify commercial use of this material in suspension components.

Justification

Automakers are under increased pressure to reduce CO₂ emissions and improve fuel economy through

increased CAFE standards. Because of its higher strength, B206 alloy structures have the potential to reduce vehicle mass, which is directly linked to improved CAFE and vehicle performance. There is also a potential for cost savings, because less material would be required when compared to conventional aluminum castings.

Program and Deliverables

This project will take 30 months to complete and will proceed in four stages. Below is a description of the deliverables for each of the four phases of the project.

Phase 1

The main alloying elements in 206 alloy (Cu, Mg, Mn) will be varied in a series of statistically designed experiments. Test bars will be cast at each composition and heat treated to the T4 and T7 tempers. Hot-crack test castings will be made to study the effect of alloy composition on castability, and 'wedge' castings will also be poured to determine the effect of solidification rate on tensile properties. These tests will determine the effect of alloy composition on mechanical properties and castability, and will allow design and casting engineers to better tailor mechanical properties for any specific application. The minor impurity elements (Fe and Si) will also be varied to determine the effect of these elements on mechanical properties. It appears that the maximum limits for Fe and Si, presently listed in the AA specifications for the 206 alloys, are lower than necessary for most automotive applications. Increasing these limits by a modest amount would reduce the cost of the alloy. These tests will be conducted at the Research and Development Center of Alcan International and at Nemak.

Phase 2

Parts made in 206 alloy are immune to stress corrosion in the T4 and T7 tempers. Parts that have been aged to peak strength (T6), however, are susceptible. Published information on other Al-Cu-Mg alloys suggests that relatively short aging times may induce stress corrosion, and that the susceptibility to stress corrosion may occur before any change in hardness is found. For example, the temperatures and times used in powder coating may

cause a problem. This part of the study will map out the dangerous areas which must be avoided. It will also examine alternative T7 treatments, to see if there is a way to improve material properties (especially elongation) in this temper. The use of alternative methods to test for stress corrosion resistance will also be evaluated. The standard test is cumbersome, and takes 30 days to complete. A simpler, more rapid, test is desirable. This phase of work will be carried out at the University of Windsor in Windsor, Ontario; and at Westmoreland Mechanical Testing Laboratories. Additional support will be provided by the laboratories of Alcan International.

Phase 3

A cost model will be constructed for suspension components manufactured using different processes and materials. A General Motors FLCA forged in 6xxx alloy will serve as a mule for this economic study. The following component cases will be considered:

- forged 6xxx alloy
- sand cast B206 alloy
- semi-permanent mold cast B206 alloy
- permanent mold cast A356 alloy

Creative Concepts will assist the project group in formulation of the cost models in this portion of the study. Sync Optima will also do FEM studies of the different cases, to determine changes required in the design (and weight) of the control arm as the material is changed from the base condition (forged 6xxx alloy).

Phase 4

In this final stage of work, control arm 'Mule' castings will be manufactured by the composite precision sand casting process at Nematik. Semi-solid cast parts will also be made at Mercury Castings. In AMD 305 parts were made and heat treated to the T4 temper. In this new work, additional castings will be made and tested in both the T4 and T7 tempers. In this way, a complete set of mechanical property data will be obtained for the castings.

For this portion of the project, the compositions used to produce castings will be the optimum alloy compositions mapped out in phase 1 of the project.

Westmoreland Mechanical Testing and Research will do testing of castings made in this phase of work.

Measurable Success Indicators

The successful results desired from each of the four phases of work are outlined below:

Phase 1

Mechanical properties as a function of cast material composition will be provided, allowing automotive design engineers to optimize component properties at lowest possible cost. Information will be provided that may allow us to increase upper limits for dissolved Si and Fe, and reduce costs in 206 alloy.

Phase 2

Optimum heat treatment schedules, which avoid stress-corrosion problems, will be established and recommended. Simple and rapid tests for stress-corrosion susceptibility will also be evaluated.

Phase 3

Cost models will be provided for the production of suspension components using several manufacturing processes and different materials. This model will assist automotive design engineers to optimize component performance and, at the same time, to help realize production cost savings.

Phase 4

Control-arm castings will be produced using two different casting processes and a complete battery of material property tests of the components will provide the technical database needed to design, manufacture and use suspension components cast in B206 alloy.

Technical Results

The results of the phase 1 casting trials have been used to map out the range of mechanical properties that can be obtained from B206 alloy castings. For permanent-mold test bars, which have a relatively

rapid solidification rate (20-30 seconds), the tensile properties found in the T4 temper are shown in Figure 1. The irregular polygon in this figure indicates the variation of tensile properties (UTS or ultimate tensile strength, YS or yield strength in MPa, and elongation) that one may expect as the composition is varied between the upper and lower limits for this alloy in the Aluminum Association specifications. The amounts of Cu, Mg, Mn, Fe and Si in the alloy were all allowed to vary.

The corresponding range of mechanical properties available in the T7 temper is indicated in Figure 2.

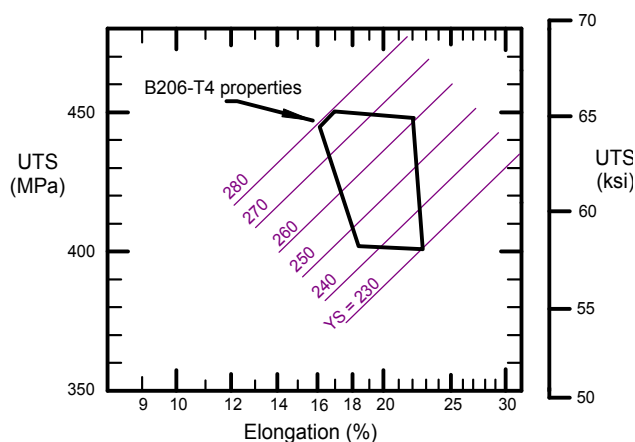


Figure 1. B206-T4 tensile properties.

In addition to these results, two of the Alcan alloy compositions were poured into an end-chill mold. Tensile samples were cut at three distances from the chill (ranging from 12.5 to 50 mm (½ to 2 inches). The tensile properties obtained from these castings are shown below, together with data published for the more commonly used aluminum casting alloys.

The solidification time is indicated in this figure by numerical values for the secondary dendrite arm spacing (SDAS), or the cell size in the case of B206 alloy. (The data for A357 alloys is for heavily chilled sections of aerospace castings only.) It can be seen that B206 alloy exhibits mechanical properties superior to the conventional Al-Si-Mg and Al-Si-Cu casting alloys.

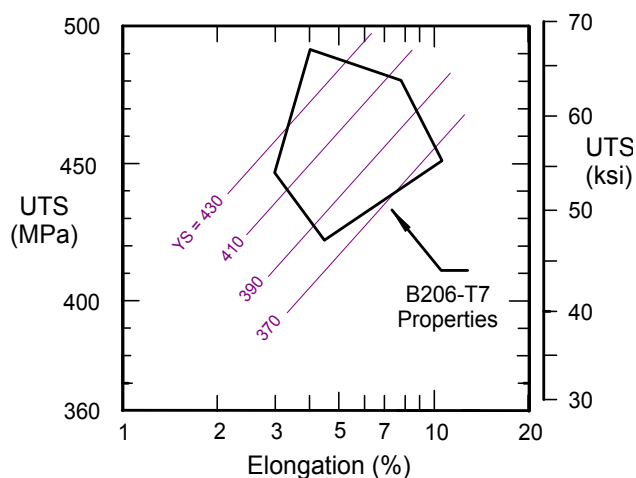


Figure 2. B206-T7 tensile properties.

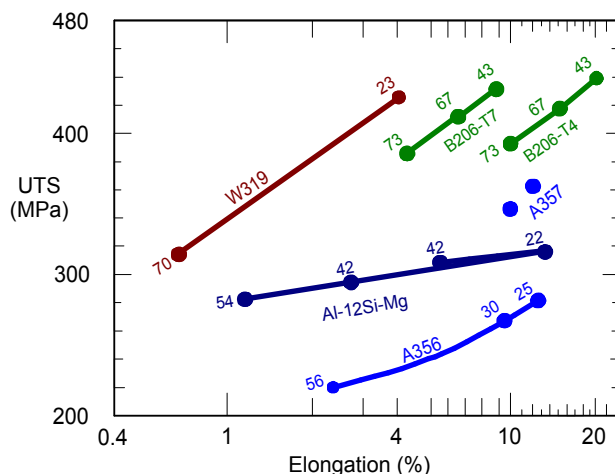


Figure 3. Range of mechanical properties in five aluminum casting alloys.

A number of B206 alloy samples were aged and tested for intergranular attack by corrosion. A test procedure outlined in Mil Spec MIL-H-6088 and ASTM specification G110 was used. This procedure correlated well with the results of a standard alternate immersion test in 201 alloy,² and so it was adapted for use in phase-2 of this study. The average depth of the intergranular attack by corrosion (in microns) is plotted in Figure 4, as a function of aging time and aging temperature.

In this plot the safe aging conditions are indicated by the hatched areas. (These areas indicate aged

² M.S. Misra and K.J. Oswalt: "Corrosion Behavior of Al-Cu-Ag (201) Alloy," *Metals Engineering Quarterly*, Vol. 16, pp. 39-44 (1976).

samples where the average intergranular corrosion depth was less than 20 microns deep.) The areas of worst corrosion attack are 'in between' the safe areas, at aging temperatures between 100 and 180°C.

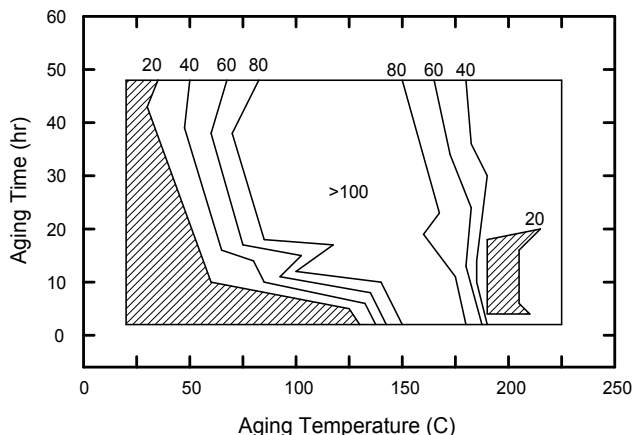


Figure 4. Average depth of corrosion.

In Phase 2 of our program, immersion stress-corrosion tests were conducted in accordance with ASTM G47-98 standard. Specimens were all naturally aged for 3 days and artificially aged for different durations at temperatures between 100 and 225°C. The stress-corrosion-cracking (SCC) life contour plot is provided in Figure 5 as a function of artificial aging temperature (T) and time. The worst stress corrosion life occurred between 100 and 175°C, which is consistent with intergranular corrosion results outlined in Figure 4. More analysis will be conducted for possible correlation between the results from the two test methods.

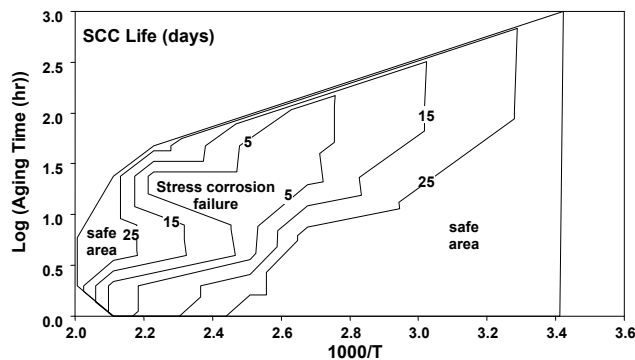


Figure 5. Stress corrosion cracking life contours as a function of artificial aging time and temperature.

Contour plots of tensile properties after artificial aging at temperatures between 100 and 225°C for various durations are presented in Figure 6. Highest UTS and elongation are obtained at an artificial aging for 12-24 hours at 125°C. A small set of experiments are planned at Alcan Laboratories to obtain more detailed results.

Presentations and Publications

The results from this project so far have generated two presentations and papers:

1. G.K. Sigworth, J.F. Major: "Factors Influencing the Mechanical Properties of B206 Alloy Castings," **Light Metals 2006**, pp. 795-799, 2006 (presented at 2006 TMS Annual Meeting).
2. J.F. Major, & G.K. Sigworth, "Chemistry / Property Relationships in AA 206 Alloys," paper 06-029, **AFS Transactions** (presented at 2006 AFS Congress).

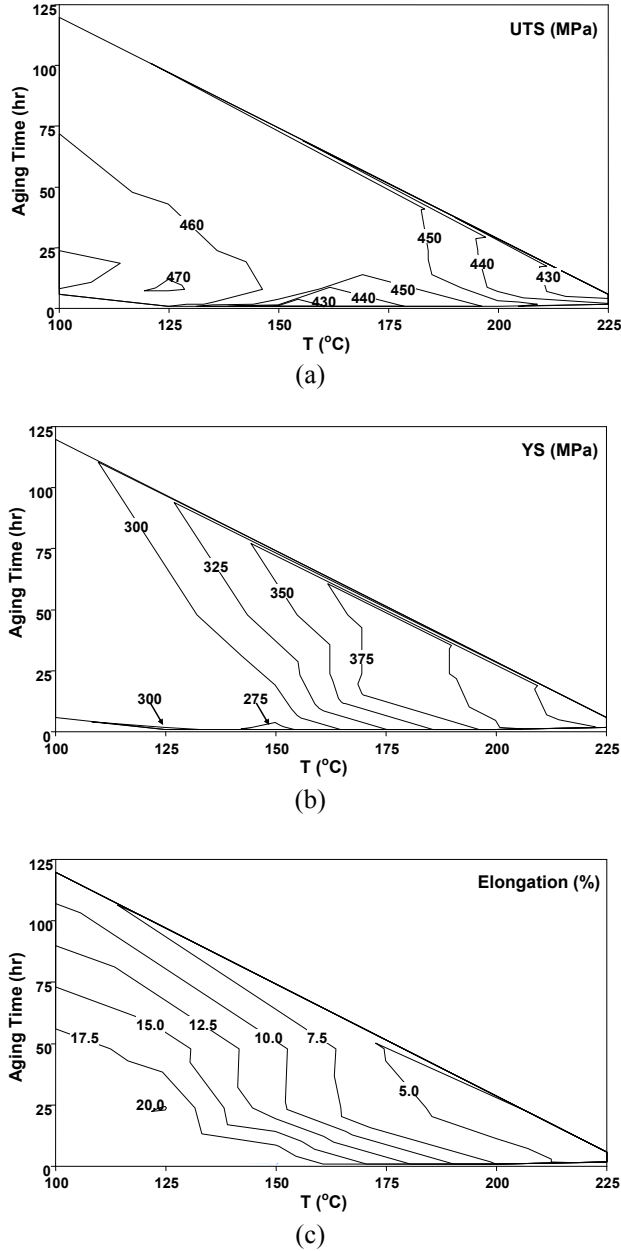


Figure 6. Contour plots for (a) ultimate tensile strength, (b) yield strength and (c) elongation as a function of artificial aging time and temperature.

- i Denotes project 405 of the Automotive Materials Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.
- ii Denotes project 302 of the Automotive Materials Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.

G. Structural Cast Magnesium Development (SCMD - AMD 111ⁱ)

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Contract No.: FC26-02OR22910

Objective

Overcome technical and manufacturing issues (high-integrity castings, corrosion & joining) that limit the lightweighting application of structural cast magnesium (Mg) automotive components. Then, demonstrate the successful application of a magnesium engine cradle in a volume production-type vehicle.

Approach

- Improve the scientific understanding of Mg alloys.
- Develop a cost model that compares cast Mg chassis component costs to other materials and processing techniques.
- Provide comprehensive database and design guidelines.
- Develop improved casting processes.
- Identify and/or develop methods to improve corrosion resistance.
- Improve joining technologies.
- Transfer knowledge and lessons learned to industry.
- Complete all scientific project tasks relevant to microstructure-property modeling, corrosion mitigation, joining behavior and nondestructive evaluation (NDE) methods, etc.
- Redesign an existing aluminum (AL) cradle to Mg and produce validation-ready components for testing and approval for Corvette's 2006, Job #1 requirements as shown (see Figure 1).

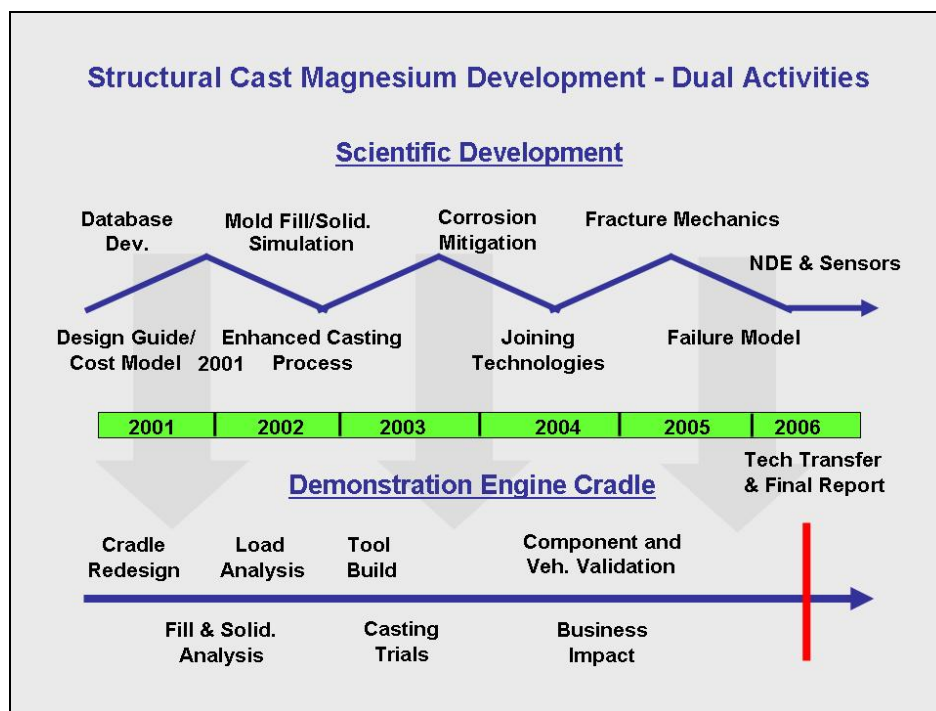


Figure 1. Dual-project path for science and Mg demonstration casting validation activities.

Accomplishments

- Completed Mg-to-Al cradle re-design and finite-element analysis (FEA).
- Produced 150 prototype components and conducted sub-system and full-vehicle validation with no issues reported.
- The Mg cradle achieved a 5.5 kg reduction in weight (35%) with respect to the current Al cradle now used in production applications (See Figure 2).
- Completed mechanical-property and microstructural characterization of numerous Mg-alloy production components.
- A new high-temperature creep-resistant alloy AE44 was developed by participating team member Hydro Magnesium, which successfully completed bench and vehicle testing.
- CANMET's corrosion studies showed the need for dissimilar-metal isolation requirements.
- CANMET's bolt-load retention (BLR) analysis demonstrated that the cradle attachments would meet vehicle performance requirements.
- SCMD team developed and implemented a successful galvanic-corrosion mitigation strategy which proved successful in bench and vehicle validation testing. SCMD database material testing was completed and provides computer-aided engineering (CAE) properties.
- Mississippi State University (MisSU) and Sandia National Laboratory (SNL) completed material-testing quantitative microstructure characterization and successfully exercised their multiscale static and fatigue models.
- Lawrence Livermore National Laboratory (LLNL) completed fabrication of several ASTM E5505 Radiographic Inspection Standards (RIS) which will improve casting evaluation sensitivity.
- The project demonstration cradle passed all validation requirements with no issues and is now in volume production on the 2006 Z06 Corvette.

- SCMD and MCPP (see report 2.H) project teams developed and published a Magnesium 2020 document which outlines a North American strategic vision (from 2005 through the year 2020) for automotive weight reduction using Mg components.
- The SCMD database has been improved with a new navigation system and additional property inputs.
- The list of SCMD publications and presentations are included in the final report published 8/29/06.

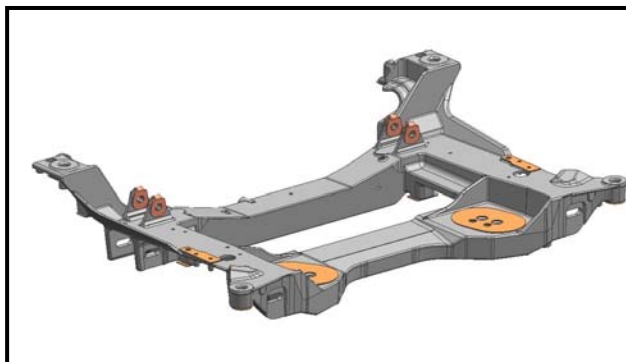


Figure 2. Machined Mg cradle.

Future Direction

- The SCMD project made significant scientific and application progress, but this project alone is insufficient for Mg to realize its full vehicle weight-saving potential without a dedicated long-term vision to focus future research and development efforts. Therefore, the scope of the SCMD project was increased on 3/9/05 to develop an industry vision that outlined the potential to increase the use of magnesium (North American Automotive) from 12 pounds (5.5 kg.) / typical vehicle in 2005 to 250 pound (114.6kg.) /typical vehicle in 2020. The document *Magnesium Vision 2020* was completed and included with the SCMD project report published on 8/29/06. Copies of the *Magnesium Vision 2020* document are available through the USCAR Office.
- The SCMD Core Team completed the preliminary investigation of the low-pressure permanent-mold (LPPM) casting process to cast a duplicate Mg cradle by this alternative casting process. Future work will continue with the High-Integrity Mg Automotive Casting (HI-MAC) project (see 2.J).

Introduction

The SCMD project focused on resolving critical issues that limited the large-scale application of Mg castings in automotive components. The project activities combined the science and manufacturing technology necessary to implement front and rear structural cradles. Such components offer all of the difficult manufacturing issues, including casting process (high-pressure die, semi-solid, low-pressure, squeeze, etc) and joining, along with harsh service environment challenges, such as corrosion, fatigue, and stress relaxation associated with fasteners. The project team included personnel from:

- The “Big Three” automotive companies
- 34 companies from the casting supply base
- Academic personnel

- Independent testing and research labs
- American Foundry Society (AFS)
- Technical Associations
- Oak Ridge National Laboratory (ORNL)
- Sandia National Laboratory (SNL)
- Lawrence Livermore National Laboratory (LLNL)
- Natural Resources Canada (CANMET)

Industry Participants

An existing Al engine cradle (that is currently in production use) was redesigned for two different Mg casting processes: high-pressure die casting (HPDC) and low-pressure permanent-mold (LPPM). Utilization of computer simulations (prior to tooling design) indicated good correlation of casting fill

operation (and their effects) to actual production experiences (see Figure 3).

Tooling and castings were made for both processes. Several hundred HPDC production prototype castings were distributed to SCMD project participants and to the GM Corvette Team for the rigorous testing procedures that were required for the HPDC cradle (see Figure 4). Based on the results of the ongoing tests, the Corvette Team decided to start a parallel production program for the

implementation of using a Mg cradle for the 2006 Z06 Corvette.

The LPPM process (see Figure 4-A) will continue further development with the HI-MAC project approved on 4/1/06 (see 2.J).

Importance/Significance: Utilization of up-front computer modeling (used for both HPDC and LPPM processes) resulted in significant savings (time and costs) and eliminated casting defects in the initial castings. Based on the prototype castings produced

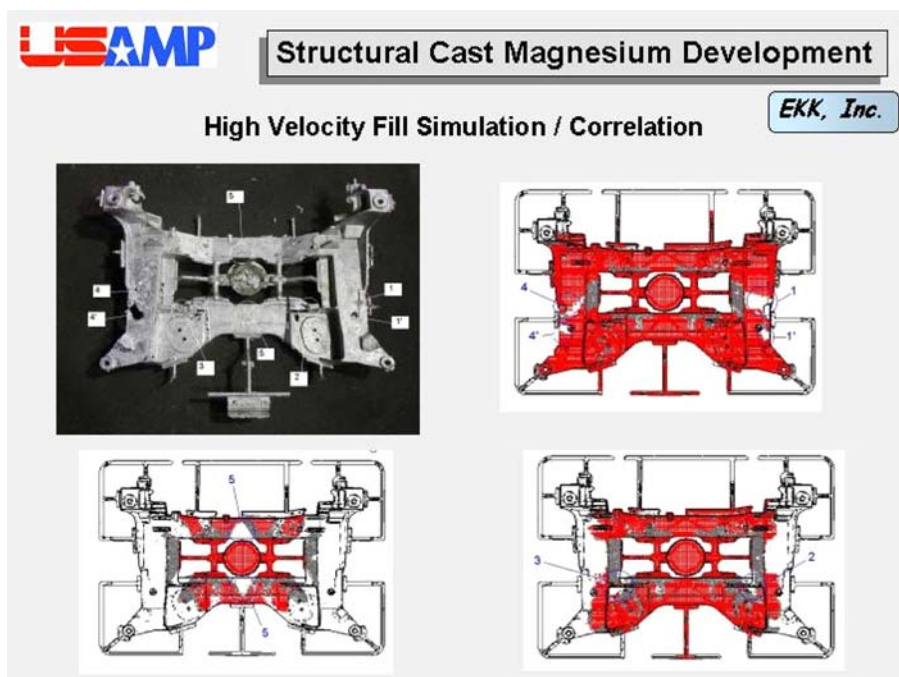


Figure 3. EKK, Inc. cavity-fill simulations show excellent correlation with short-fill HPDC castings.



Figure 4. Initial machined HPDC cradle castings.



Figure 4-A Initial LPPM Mg cradle.

by both processes, there was an estimated 35% weight savings in the Mg cradle versus the current Al production part. The investigation of producing the same casting by the two different processes (HPDC and LPPM) has a great potential for the utilization of existing Al casting companies to expand their operations into Mg without huge capital and facility expenditures.

Project progress/status vs. targets

The project targets for 2006 were to complete the outstanding Statements of Work for the final project report to meet Job #1 2006 objective for Corvette (completed), and to complete the Magnesium 2020 document (completed).

Remaining Technical Challenges and Plans

The SCMD project completed the outstanding Statements of Work, and the Final Report was published and distributed to all project participants on August 29, 2006.

Milestones

Cooperative Agreement

Mg front cradles (HPDC process) passed all bench and vehicle testing; actual testing results coincided with predicted computer-modeling techniques. All tasks were completed on time to meet Corvette's evaluation of installing a similar Mg cradle for Job #1-2006 production vehicle.

A new high-temperature, creep-resistant alloy AE44 was developed by a participating project team member who successfully completed bench and vehicle testing.

Detailed quantitative microstructural characterizations were completed for other production components cast with AZ91D, AM 50 and AM 60 Mg alloys. CANMET's corrosion studies showed (see Figure 6) the need for dissimilar metal isolation. CANMET's BLR analysis demonstrated that the Mg cradle attachments would meet vehicle performance requirements.

Cooperative Research and Development Agreement (CRADA)

ORNL—ORNL completed the investigation of modeling software from four of the supply teams. The results of the investigation were applied to the ORNL models using current commercial software; ORNL completed the investigation of the effects of using die lube for HPDC and LPPM operations (see Figure 5).

Importance/Significance: These investigations (real time and software proven) indicated that gas can be generated from the lube when molten metal (higher temperature) is introduced into the mold cavity. The gas then disperses throughout the casting, causing various types of porosity defects.

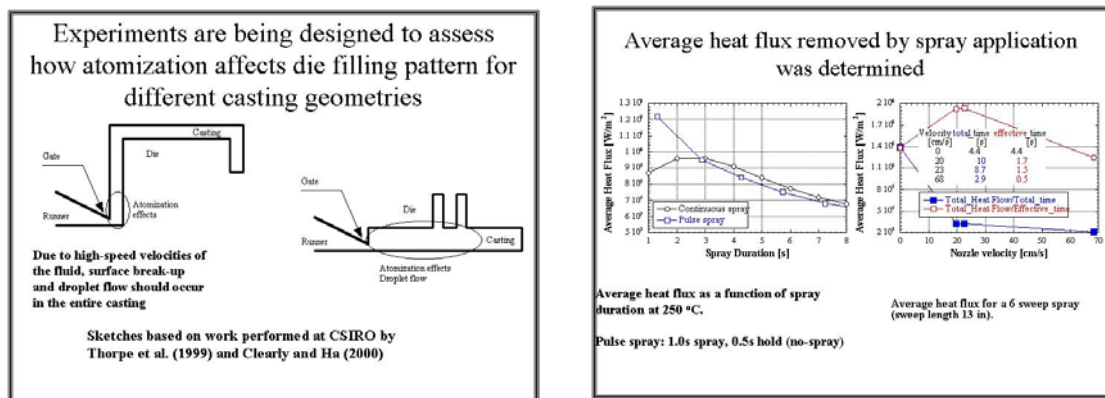


Figure 5. ORNL die-lube investigation work.

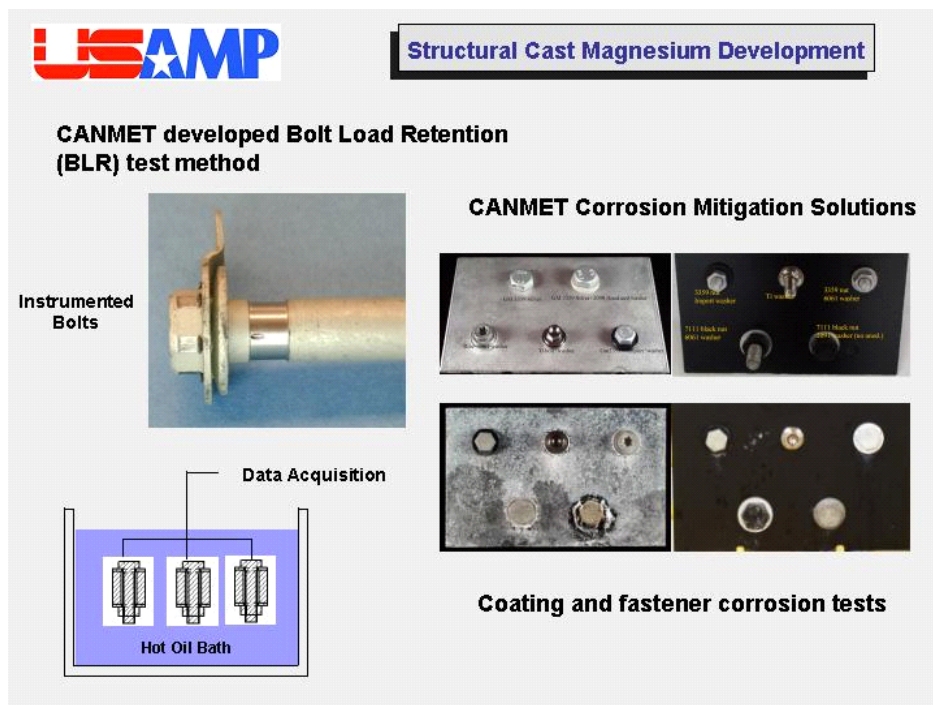


Figure 6. CANMET bolt-load retention testing and corrosion studies developed knowledge required for product implementation.

SNL/MisSU—SNL coordinated the collection of project data from all the SCMD project testing sites and then used the data to expand the mathematical “failure model” (see Figure 7).

Importance/Significance: Designers can use the multiscale fatigue model to develop castings with the accurate knowledge of providing known failure points.

LLNL—LLNL completed the fabrication of several ASTM E505 Reference Quality Indicators that will improve casting evaluation sensitivity (see Figure 8); performed radiographic analysis of production parts and test samples to determine discontinuity types and grades at predicted high-stress locations; investigated the possibility of using fiber-optic, in-mold thermal monitoring for HPDC

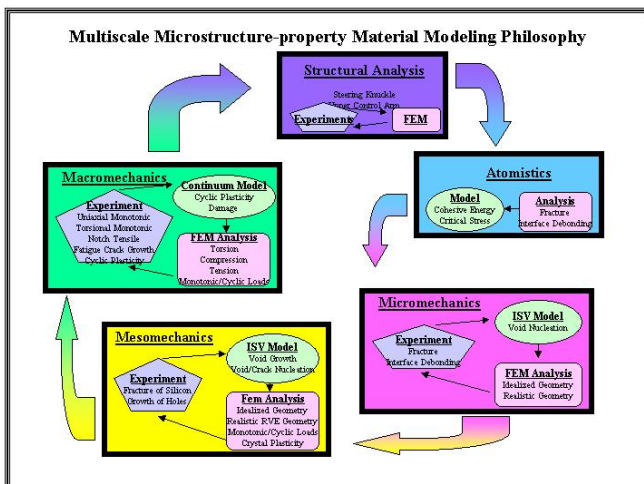


Figure 7. SNL damage model for simulating component material properties.

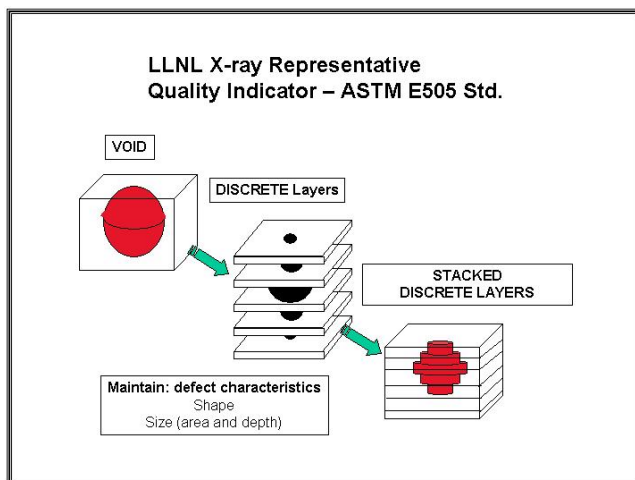


Figure 8. LLNL development activities.

in a high-volume production facility; worked with suppliers to provide a system to detect impurities in the metal that is charged into the furnace.

Importance/Significance: All of the above procedures and investigations will provide more consistent and measurable standards that are required for improved quality control and to improve the safety critical components that are cast in Mg

Academia participants: Academia participation in the SCMD project was involved with: the investigation of and characterization of crack nucleation and growth; the investigation into the

cause of casting defects and the ability to separate gas and shrinkage effects that are generated (in the casting) by the various processes. (See Figure 9)

Importance/Significance: The importance of understanding the crack nucleation and the results of gas generated in Mg castings will help to provide tools to manufacturing (or change process parameters) to eliminate casting defects. Both of these investigations by academia worked with the information supplied by ORNL and sample parts provided by the manufacturing team. The understanding of the gas effects in castings, generated by die lube is a major breakthrough in understanding defects in Mg castings.

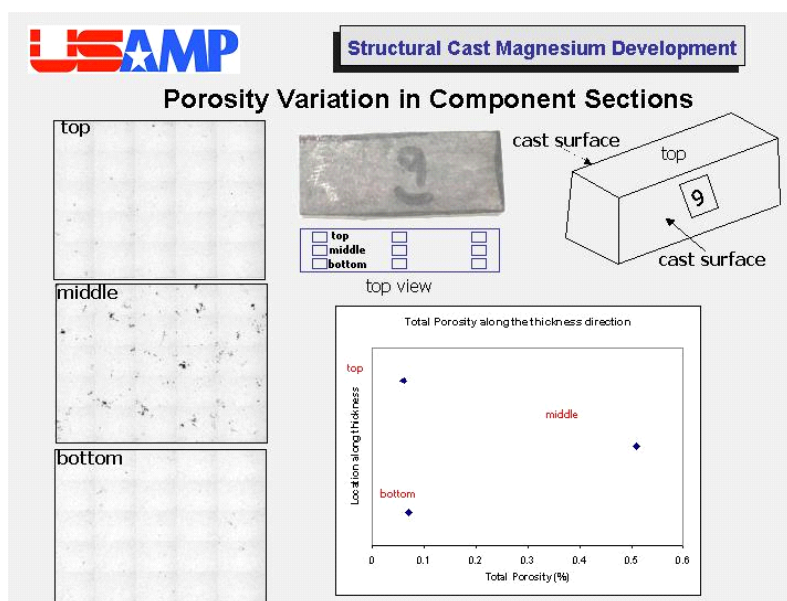


Figure 9. Georgia Institute of Technology characterization of AE44 alloy HPDC cradle section.

Project Benefit

The DOE and U.S. industry benefits derived from the successful completion of this CRADA includes vehicle mass savings for ground and air transportation, leading to reduction in fuel consumption, emissions, and less dependence on foreign oil.

The North American (NA) auto industry currently uses approximately 12 pounds (5.5 kg) of Mg per vehicle per year. The ability to significantly increase Mg usage will help the auto industry meet future

Federal Corporate Average Fuel Economy (CAFE) targets and reduce exposure to CAFE penalties. Cast Mg structures have the potential to reduce 100 kg of vehicle mass, which could reduce emissions by 5% and reduce fuel consumption by approximately 1.0 mpg (ignoring secondary mass savings).

Light-metal alloys have greater recycling value with reduced energy consumption versus plastics (including melting, machining, handling, and transportation energy requirements). The Big Three competitive global postures will increase as a result of designing and manufacturing

vehicles that offer greater consumer value. This can improve the U.S. trade balance with countries that market higher fuel efficiency vehicles than those produced in North America.

Health and environmental issues for workers are reduced during light-metal casting operations when compared to ferrous foundries and polymer-molding operations.

Participation provides the national laboratories with valuable manufacturing-development and product-application experience.

The dual purpose role of providing the national laboratories (and academia) an opportunity to develop math-based simulation models and NDE technologies, benefits both the auto industry and federal ongoing technology programs.

The preliminary studies completed by the casting of a M cradle (by low-pressure die casting) has indicated to the existing Al casting industry that the transfer of casting technology (Al to Mg casting) can be achieved at a low facility cost, and additional work will continue with the HI-MAC Project.

Conclusion

The SCMD project has proven the successful casting (and recent production use) of a Mg engine cradle is a major accomplishment for NA Mg casting industry. Most important, the project success has proven that the technical and manufacturing issues (high-integrity castings, corrosion & joining) that have heretofore limited the light weighting application of structural cast Mg automotive cradles, was successfully solved in the SCMD project.

OEM's Presentations and Publications

Approximately 315 presentations were made by SCMD Project Team Members and Principal Investigators at Quarterly Review Meetings (QRM) and OEM presentations. The QRMs held are listed below.

Year	Meeting	Date	Location
2000	QRM #1 (General Presentation to Proposed Project Participants)	05/15/2000	USCAR Office Building
2001	QRM #1 QRM #2 QRM #3 QRM #4	03/20/2001 Cancelled 09/26/2001 12/11/2001	Meridian Technologies WMTR USCAR Office Building
2002	QRM #1 QRM #2 QRM #3 QRM #4	03/29/2002 07/30/2002 09/23/2002 12/11/2002	SNL Alfred University WMTR Hayes-Lemmerz
2003	QRM #1 QRM #2 QRM #3 QRM #4	02/11/2003 05/14/2003 07/25/2003 12/09/2003	USCAR Office Building Gibbs Die-Casting Plant WMTR USCAR Office Building
2004	QRM #1 QRM #2 QRM #3 QRM #4	03/03/2004 05/26/2004 09/21/2004 12/08/2004	Hayes-Lemmerz USCAR Office Building USCAR Office Building USCAR Office Building
2005	QRM #1 QRM #2 QRM #3 QRM #4	04/07/2005 06/28/2005 09/14/2005 12/07/2005	USCAR Office Building WMTR WMTR USCAR Office Building
2006	QRM #1 QRM #2	Cancelled 08/29/06	USCAR Office Building Final Meeting

Miscellaneous Presentations:

12/7/04 Chinese Magnesium Conference and Global Collaboration at USCAR Office

10/11/05 Preliminary Review of Magnesium 2020 Document at USCAR Office

SAE World Congress Presentations

2001 through 2006: Numerous presentations by SCMD Project Chairman and OEM Representatives all properly noted in SAE Proceedings.

Representative Sample of Publications / Presentations by OEMs & PIs

Presentations

S.G. Lee, A.M. Gokhale, and G.R. Patel, "Macro-Segregation in High-Pressure Die-Cast AM60B Alloy," *Magnesium Technology 2005 Symposium*, TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

S.G. Lee, G.R. Patel, A.M. Gokhale, and Mike Evans, "Effects of Liquid Metal Gate Velocity on the Porosity in High-Pressure Die-Cast AM50 Alloy," *Magnesium Technology 2005 Symposium*, TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

A. Sreeranganathan, Soon Gi Lee, and A. M. Gokhale: "Quantitative Characterization of AM50 and AS21X Magnesium Alloys to Correlate the Variability in the Fracture Properties to Microstructure," *Automotive Alloys 2005 Symposium*, TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

Soon Gi Lee, Arun Sreeranganathan, and A.M. Gokhale: "Simulation of Mechanical Behavior of Die-Cast Magnesium Alloy Based on Three-Dimensional Porosity and Finite Elements Method," *Symposium on Computational Aspects of Mechanical Properties of Materials: Meso-Scale and Continuum Modeling*, TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

Soon Gi Lee and A.M. Gokhale: "On the Formation of Gas (Air) Induced Shrinkage Porosity in Pressure Die-Cast AM60 Mg-Alloy," *Symposium on Defect Formation, Detection, and Elimination During Casting, Welding, and Solidification: Processing, Microstructure, and Properties*, *Materials Science and Technology 2005* (MS&T 2005), Pittsburgh, PA, September 26, 2005.

Soon Gi Lee, G.R. Patel, and A.M. Gokhale: "Variability in Tensile Ductility of High-Pressure Die-Cast AE44 Mg-Alloy," *Symposium on Defect Formation, Detection, and Elimination During Casting, Welding, and Solidification: Processing, Microstructure, and Properties*, *Materials Science and Technology 2005* (MS&T 2005), Pittsburgh, PA, September 26, 2005.

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ⁱ Denotes project 111 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.

H. Magnesium Powertrain Cast Components (AMD 304ⁱ)

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Contract No.: FC26-02OR22910

Objective

- Demonstrate and enhance the feasibility and benefits of using magnesium (Mg) alloys in place of aluminum (Al) in structural powertrain components, thereby achieving at least 15% mass reduction of the cast components.

Approach

- Identify, benchmark, and develop a design database of the potentially cost-effective, high-temperature Mg alloys and, using this cast-specimen database, select the alloys that are most suitable for the Mg components. (Task 1)
- Design, using finite-element analysis (FEA), an ultra-low-mass engine containing potentially four Mg components (cylinder block, bedplate, structural oil pan, and front engine cover) using the most suitable low-cost, recyclable, creep- and corrosion-resistant Mg alloys. (Task 2)
- Create a cost model to evaluate alloy, manufacturing, and technology costs to predict the cost-effective performance of the engine. (Task 2)
- During the execution of Tasks 1 and 2, identify and prioritize the critical gaps in the fundamental science of Mg alloys and their processing that are barriers either to the progress of the project or to the use of Mg in future powertrain applications. Seed-fund the most critical research, and promote additional identified needs to support further development of the Mg scientific infrastructure in North America (NA), thereby enabling more advanced powertrain applications of Mg. This will be one aspect of the technology-transfer deliverables of the Magnesium Powertrain Cast Components (MPCC) project. (Task 3)
- Note that before addressing Tasks 4–6 and funding Task 3 research, an in-depth review of the engine design, including performance and durability predictions, alloy requirements and measured alloy properties, cost model, and predicted mass reduction was to be conducted. Passing this gate review was necessary for entry into the second half of the project, which has the goal of demonstrating/validating the engine design with respect to castability, manufacturability, performance, durability, and cost.
- Refine the engine component designs as necessary (updating to match the properties of the alloy selected for each component), design and build tools and patterns, and cast the engine components. (Task 4)

- Excise specimens from the cast components and develop a full mechanical and corrosion design database for the alloys. Create an original equipment manufacturer (OEM)—common material specification for Mg powertrain alloys. (Task 5)
- Assemble complete powertrains, dynamometer-test the components, and conduct end-of-test teardowns. Refine the cost model to support determining the cost-effective performance of the engine. (Task 6)

Accomplishments

- In the years 2001-2004, Tasks 1 and 2 were completed. A successful gate review for entering Phase II was accomplished, involving (1) the selection of alloys for each Mg engine component and revision of the component designs based on the properties of the selected alloys, (2) the issuance of contracts to project teams for tooling and casting each component, and (3) the selection of five basic-research projects in support of the objectives of Task 3.
- In 2005, substantial progress was made to accomplishing the objectives of Task 4, with the completion of component tooling design and build and the initiation of casting trials to produce the cylinder block, the structural oil pan, the front engine cover, and the rear seal carrier.
- The 2006 accomplishments follow.
- The prototype casting development phase for the cylinder block was completed. Fonderie Messier (a division of Honsel, Inc.), in Arudy, France successfully cast Australian Magnesium Technologies alloy SC-1 into sound (leak-free) cylinder blocks using low-pressure sand casting. With the close of the 2006 fiscal year, the casting of “production” cylinder blocks was commenced. This significant success leads the way to full engine testing of the Mg-intensive engine in early 2007.
- Structural oil-pan castings were completed. Spartan Light Metal Products high-pressure die-cast the pans using Dead Sea MRI 153M alloy. After machining and leak testing, the castings were then delivered to Hitachi America for friction-stir welding (FSW) of the cover onto the oil pan reservoir.
- The feasibility of FSW the cover onto the oil pan reservoir was demonstrated. This success validated the project plan to simplify the tooling for the structural oil pan by removing nine bolts hole/flange sets and contributed to being able to cast this very difficult part.
- The front engine-cover castings were completed by high-pressure die casting them at Interment using the Dead Sea MRI 230D alloy. These parts were machined and delivered for engine testing.
- The rear seal carriers were successfully thixomolded by Thixomat using Dead Sea MRI 153M alloy. This is the fourth of the four Mg components designed and cast in the project of the Mg-intensive engine.
- The wear-resistant coating to be used in the engine cylinder bores passed the honing adhesion test. This success was critical for the project strategy of using coatings, rather than liners in the bores.
- Coolant corrosion testing was completed to select a coolant for engine testing. The coolant selected demonstrated improved corrosion inhibition with the Mg cylinder block for both heat-rejecting surface conditions and galvanic corrosion.
- Of the five basic-research projects in support of the Task 3 objectives, which were launched in previous years, one was completed (Computational Thermodynamics and Phase Equilibria - Penn State University) and the other four are making good progress: Hot Tearing Susceptibility - CANMET; Creep Mechanisms - the University of Michigan at Ann Arbor; Corrosion and Corrosion Mechanisms to the Universities of Michigan at Dearborn and Ann Arbor; and Recycling of Creep-Resistant Alloys - Case Western Reserve University.
- The patent application for the structural details of the Mg cylinder block remains in prosecution at the U.S. Patent and Trademark Office (USPTO).

Future Direction

- Complete casting and machining of the cylinder block, conduct sub-assembly of Mg components, with documented machining observations for each of the Mg components to comprehend any potential differences between the chosen Mg alloys and Al.

- Excise specimens from cast Mg engine components and test to create an excised-specimen property database of the three selected Mg alloys, which will complement the cast-specimen database completed during Phase I.
- Complete assembly and dynamometer testing, teardown, and analysis of the Mg-intensive engines.
- Input data from all stages of the manufacture of the die-cast oil pan and front engine cover and the sand-cast cylinder block into the cost model to determine the cost-effective performance of the Mg-intensive engine.
- Complete the four remaining basic-research projects to their respective completion dates.
- Complete the project by September 30, 2007.

Introduction

The use of Mg alloys to reduce the mass of automotive components has grown rapidly. NA parts include instrument panels, cross-car beams, seat frames, steering wheels, intake manifolds, valve covers, transfer cases, numerous small brackets and, most recently, the Mg engine cradle for the Z06 Corvette. In Europe, Mercedes-Benz has introduced an automatic transmission case and BMW has introduced a unique, inline, 6-cylinder engine. The BMW “composite” engine comprises an Al-alloy inner casting around which is cast a Mg shell. The Al “inner” provides the performance requirements such head bolt threads, structural stiffness, and housing the engine coolant. What remains to be determined is the feasibility of an all-Mg cylinder block.

The Magnesium Powertrain Cast Components (MPCC) Project was organized to realize the vision of a Mg-intensive engine (with an all-Mg cylinder block) that is cost-effective, light weight, and meets the manufacturability and durability requirements of the automotive industry.

To determine the feasibility of the Mg-intensive engine, MPCC Project team redesigned a V6 engine from Al to Mg. The engine chosen was the 2.5/3.0L Ford Duratec, which is shown in Figure 1. A production engine was chosen in order to allow production parts such as the valve train to be used without modification. While this limited the design freedom for the Mg-intensive engine, the economics of the “green field approach” were prohibitive.

Designing a V block in itself was a significant technical reach for Mg, relative to an in-line block because through-bolting could not be used.

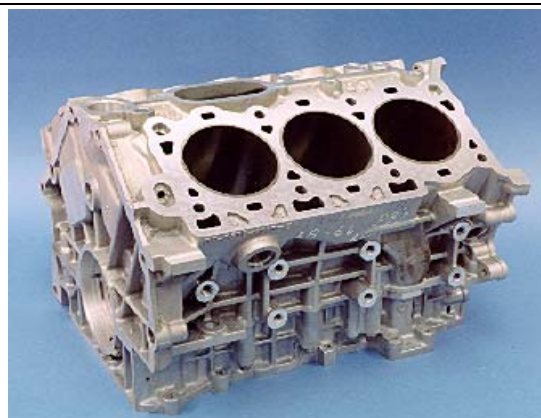


Figure 1. Production V6 Duratec block and bedplate.

Additional technical challenges anticipated included having structural stiffness, stability and durability at the operating temperature; cooling the engine with non-corrosive coolant and preventing galvanic corrosion due to fasteners and gaskets; and selecting a suitable bore/piston/ring system.

Though initially intended to contain four Mg components: the cylinder block (CB), the bedplate, a structural oil pan (SOP), and the front engine cover (FEC), the final design became that of a deep-skirt block without a bedplate.

The MPCC project was launched in January 2001 and implemented in two phases. In Phase I, the engine design was completed based on available alloy property data and used to determine the alloy property requirements for each Mg component. Additionally, several high-temperature Mg alloys were cast and tested to identify those that would be most suitable for the engine components. In October 2003, the project team conducted a successful review of its Phase I deliverables and subsequently launched Phase II, the completion phase of the project.

The main objective of Phase II is to validate the Mg-intensive engine design by casting the parts and conducting engine tests. The CB, SOP, FEC and the rear seal carrier (RSC) have been cast and engine testing is anticipated in early 2007. The other major Phase II objective is to launch and complete projects in critical basic research for advanced Mg powertrain applications. Research in these areas will strengthen the infrastructure for Mg research in NA, thus contributing to the realization of Mg-intensive powertrains.

The MPCC project team will complete the project in September 2007. This is later than originally planned because of the time required to solve the design challenges for the Mg CB which were due to the high coefficient of thermal expansion (CTE) of Mg (the solution resulted in a patent application) and difficulty in casting sound components, in particular the CB. Progress was hard, but in 2006 success was achieved for casting all of the Mg components.

Engine Components

The mass-reduction target set by the MPCC project team was 15% for the cast Mg components. The final design achieved a much greater mass reduction. The final design contains the following Mg components: the cylinder block (CB), the structural oil pan (SOP), the front engine cover (FEC), and the rear oil seal carrier (RSC). It also contains cast-iron crank bore inserts and bearing caps. A description of each component and the progress made toward tooling design, build, and casting follows.

Cylinder Block: The Mg CB is based on the Al 3.0 liter (L) block, but with bore diameters corresponding to a 2.5 L. This increase in cylinder wall thickness reduced bore distortion. The Al CB and bedplate was replaced by a deep-skirt CB and no bedplate. Bearing caps were bolted to the crank bore inserts in the CB bulkheads, see Figure 2.

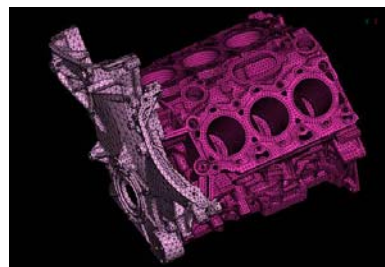


Figure 2. The Mg-intensive design: block and front engine cover.

Fonderie Messier, in Arudy, France is low-pressure casting the Mg CB using SC-1, a sand-casting alloy produced by Australian Magnesium Technologies. The block is cast in pan-rail up position with cast-in-place pearlitic ductile-iron crank bore inserts.

Three dozen “prototype” castings were made in the course of developing the gating and runner system and tuning the casting parameters. The major casting challenges were shrinkage and gas defects in the main oil gallery and the clean-oil line. These were eliminated but some cosmetic weld repair is necessary.

Sound “prototype” CB’s (passed X-ray inspection and post-machining leak testing) were achieved at the end of 2006. Thirty “production” castings are being produced in support of the engine test program. A partially-machined casting is shown in Figure 3.

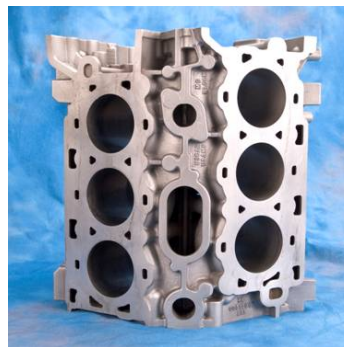


Figure 3. Partially- machined Mg block.

Cylinder-Block Bore Treatment: The MPCC strategy for the cylinder bores is to use a wear-resistant, thermal-spray coating. Successful adhesion test results were obtained. Honing development is progressing using “prototype” CBs. These were bored and the bores were prepared for coating by a roughening treatment. It is necessary that the “production” blocks do not have pinhole porosity of the type shown in Figure 4 lest it interfere with the quality of the coating.

Coolant Selection: Selection of the coolant for engine testing has been completed. Four coolant formulations, one from each of the major coolant suppliers, were tested with SC-1, the CB alloy. The coolants were developed by suppliers based on the results obtained in the first round of coolant testing, during Phase I of the project.

On the basis of the double-blind test results shown in Figure 5, coolant 2 was selected for the engine tests. All of the Phase II coolants performed better than the Phase I coolant formulations in the ASTM D4340 hot-surface corrosion and ASTM D1384 galvanic-corrosion tests. Mg still corroded in the best coolant somewhat more than Al did in the same test. The corrosion behavior of Mg alloys continues to be a high-priority research area: see Task 3 research.

Head Gasket: Dana Corporation designed the head gasket for the Mg engine. The 3-layer design contains a wave stopper sandwiched between the two active layers. The final-design materials and geometry are the result of FEA simulation for 100% and 70% bolt load cases at assembly and operating conditions. The load distribution is good, but fine tuning of the sealing pressure remains to be done. Analysis with steady-state temperature maps is in progress.



Figure 4. Pinhole porosity exposed by boring.

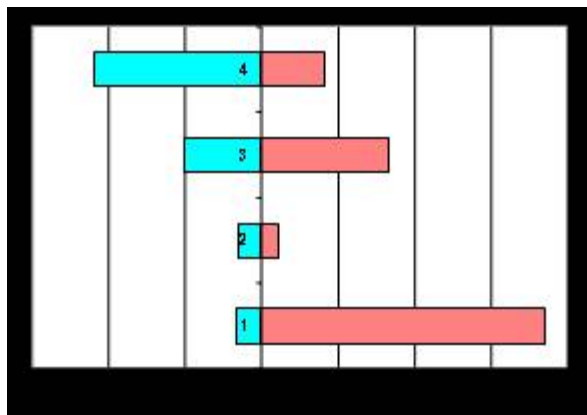


Figure 5. Corrosion results for D4340 (left) and D1384 (right) showing that coolant 2 has the best overall performance.

Structural Oil Pan: High-pressure die casting the SOP was a major challenge. Several separate casting trials were required by Spartan Light Metal Products to obtain sufficient quality castings for engine testing and component testing. The tooling for the die was built by HE Vannatter using Spartan gating, both designs being based on simulations done by Technalysis. The casting difficulty was due to the complex geometry of this component, in particular, the sump and the slides needed for it, the arrangement and size of the ribs, and the solidification behavior of the alloy, Dead Sea Magnesium MRI 153M. Hot cracking and cold shuts were eventually eliminated after altering the die. Nevertheless, the castings were impregnated to pass leak testing. The final mass of the SOP is significantly less than its Al counterpart. A schematic of the structural oil pan is shown in Figure 6.

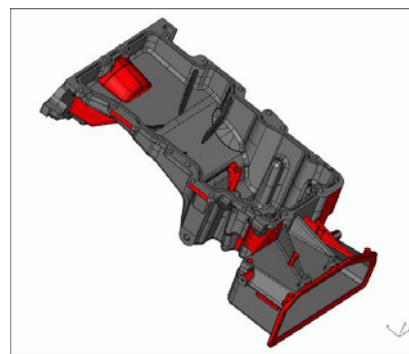


Figure 6. Schematic of Mg structural oil pan.

The sump cover of the Al production version of the oil pan is attached with eleven bolts. These were removed in the Mg design to simplify casting. Hitachi North America successfully friction-stir welded the cover in place. The use of friction-stir welding is one of several fastening methods used in various parts of the MPCC engine. The Al and Mg designs are shown in Figure 7.



Figure 7. SOP sump covers: Al production (with bolts) and Mg design (without).

Front Engine Cover: This part was high-pressure die cast by Intermet using a die built by Exco Engineering. The major redesign focus of the FEC was its noise, vibration and harshness (NVH) performance. The alloy used for the FEC is Dead Sea MRI 230D.

The cast parts showed some hot cracking. As with the SOP, hot cracking was minimized by changing the gating system and casting conditions. Other changes made to the tooling also contributed. The castings have been completed, machined and are awaiting engine testing. The FEC is shown in Figure 8.

Rear Oil Seal Carrier: The Mg version of the V-6 engine requires the use of a rear oil seal carrier. These parts were thixomolded by Thixomat. The alloy chosen was Dead Sea MRI 153M, the same

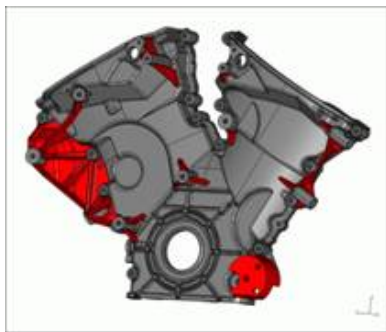


Figure 8. The Mg front engine cover design.

alloy as being used for the SOP. The first casting trials showed hot cracking, but subsequent changes to the die were made, which resulted in RSCs with excellent quality. They are awaiting engine testing. An RSC is shown in Figure 9.



Figure 9. Mg rear oil seal carrier cast by Thixomat.

Engine Dynamometer Test Program

Engine testing is the ultimate measure of the technical readiness of Mg for powertrain applications. The MPCC test program was developed to validate the engine design and its predictions about the durability and NVH performance of the engine.

The test program is based on that used for the Al Duratec. Seven tests comprise the plan. Engine teardown analysis is part of the test program. The engine tests are:

- Piston Skirt Marking
- Hot Scuff and Cold Scuff
- 150 hour deep thermal
- 300 hour high-speed durability
- 480 hour key life thermal
- 675 hour engine system test

Mechanical Property Testing and Database Development

The database architecture to house the property testing from Phase I of the project has been completed. The data that were generated in Phase I were used to select the alloys for each engine component and for design revisions. The database architecture was developed at Westmoreland Mechanical Testing & Research. Consistent with the original objective of the project, the MPCC database and the Structural Cast Magnesium Development

(see 2.G) database are of common architecture. The two databases are being combined.

The alloy property data that were produced in Phase I of the project were obtained from cast specimens. The Phase II data will come from specimens excised from the cast components. This testing began in 2006.

Task 3. Critical Scientific Needs for Powertrain Magnesium Alloys

During Phase I of the MPCC project, gaps in the science of powertrain Mg alloys and/or processing were identified and documented. These gaps are critical for future applications of Mg in automotive powertrains. It was an original objective of the MPCC project to identify such gaps and to start new, or expand existing, research in NA to address them. Five projects were launched and one has been completed. The others will be completed in 2007.

Computational Thermodynamics and Alloy Development of Magnesium Alloys: Prof. Z.K. Liu at Penn State University uses first-principles calculations to compute thermodynamics databases. They are used to predict phase equilibria in critical alloy systems including Mg-Al-Ca and Mg-Ca-Sn. An example of results from this project, the Ca-Sn binary was predicted from *ab initio* calculations and compared with experimental work from the literature. The predicted phase diagram is shown in Figure 9. This project is complete.

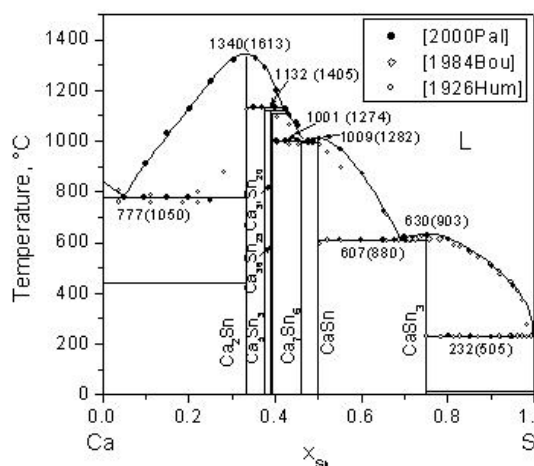


Figure 9. Calculated Ca-Sn binary from *ab initio* calculations.

Hot-Tearing Behavior of Magnesium Alloys:

Dr. D. Emadi at CANMET seeks (1) to optimize an experimental system for quantifying the hot-tearing susceptibility of Mg alloys and (2) to determine the microstructural basis for hot tearing in these alloys. Hot tearing is related to the solidification behavior of the alloy and the tendency of a particular alloy to hot tear has a large impact on its castability and the economics of the casting process. Hot tearing or hot cracking was an issue for each of the components that were cast in the MPCC project. The Mg-Al alloys being studied contain Ca and Sn. Dr. Emadi's effort addresses the impact of these alloying elements on the hot-tearing behavior of AM50 under sand-casting conditions.

Creep, Bolt-Load Retention, and Microstructural Analysis of High-Temperature Mg Alloys:

Creep is perhaps the single most important requirement for Mg alloys for use in powertrain applications. Creep is the slow plastic deformation of a material subjected to sustained load at high-temperature. Prof. W. Jones' team at the University of Michigan at Ann Arbor is developing mechanistic models and seeking the microstructural basis for the observed creep rates of the high-temperature alloys under tensile creep or compressive/bolt load conditions. The bolt-load retention system is shown in Figure 10.

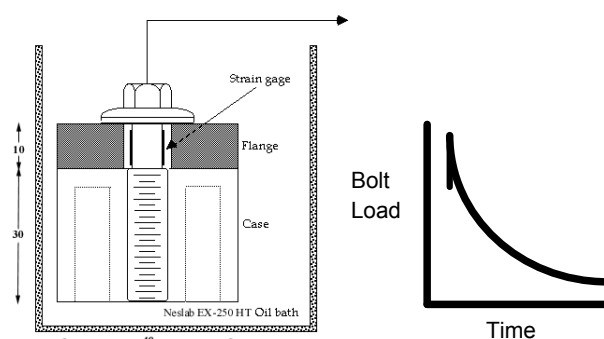


Figure 10. Bolt-load retention testing showing test assembly and typical change in bolt load with time at test temperature.

Evaluation of Mg Corrosion by Various Methodologies and Surface Composition of Magnesium Alloys by Rutherford Backscattering:

The first phase of this project was begun at the University of Michigan at Dearborn under the leadership of Prof. P.K. Mallick. All of the

high-temperature Mg alloys considered in the MPCC project were corrosion tested using several different methodologies. The differences observed among the methods were documented and extensive research was conducted to explain the differences on the basis of the operating corrosion mechanisms. The experimental configuration for simultaneously monitoring several corrosion measurement methods is shown in Figure 11. In the second phase of the work, Rutherford Backscattering (at the University of Michigan at Ann Arbor) will be used to study the corrosion interface to further reveal the microstructural basis for Mg corrosion. The results of this work will contribute to the development of improved alloys and/or improved corrosion mitigation strategies.

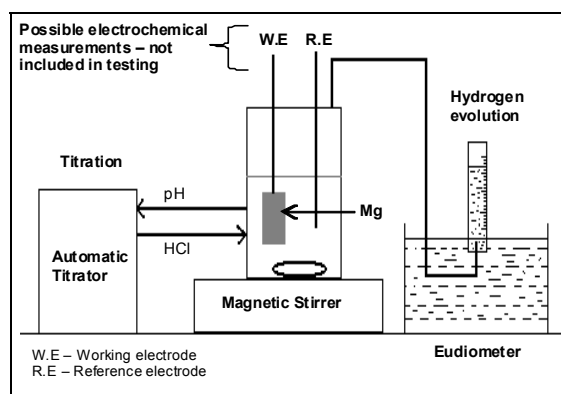


Figure 11. The simultaneous corrosion test system.

Fluxless Recycling Methods and Process Control for Creep-Resistant Magnesium Alloys: Prof. D. Schwam at Case Western Reserve University and E. Es-Sadiqi at CANMET. Recycling of current automotive Mg alloys is well understood. However, the creep-resistant alloys contain alloying elements such as Ca, Sr, Sn, and rare earths. These elements are not amenable to current flux-based recycling methods because they react with the flux. The significance of this on the practice and economics of recycling has yet to be determined. The first phase of this project produced an in-depth survey of the industry and the scientific literature to determine the recycling barriers. The second phase of the work will be research to further overcome the identified barriers.

Conclusion

The MPCC Project has made excellent progress since its inception in 2001. Project accomplishments include completion of the component designs, building and testing of the component dies, and casting the parts for use in engine dynamometer testing.

In accomplishing this work collaboratively, the MPCC project enabled sharing the costs and risks and avoided duplication of effort. It has already renewed interest in using Mg in automotive powertrains within the Mg supplier and manufacturing community as well as the automotive industry. The project is promoting greater competition and rapid development of Mg sources, manufacturing capability, and engineering expertise, and has already encouraged the development of scientific research projects into the properties, processing, and behavior of Mg at various universities and national laboratories in NA. The project team expects to complete all “bill of materials” aspects leading to the initiation of engine dynamometer testing in 2007.

Presentations/Publications/Patents

1. J.A. Hines, R.C. McCune, J.E. Allison, B.R. Powell, L.J. Ouimet, W.L. Miller, R.S. Beals, L. Kopka, and P. P. Ried, “Building a Mg-Intensive Engine: A Progress Report on the USAMP Magnesium Powertrain Cast Components Project,” 2006 Magnesium Technology Symposium of TMS, San Antonio, Texas, March 12, 2006.
2. R. Arroyave, M. Ohno, R. Schmidt-Fetzer, and Z.K. Liu, “Finite-Temperature Thermodynamic Properties of Intermetallics in the Mg-Ca-Sn System via First-Principles Methods,” 2006 Magnesium Technology Symposium of TMS, San Antonio, Texas, March 12, 2006.
3. B.R. Powell, L.J. Ouimet, G.K. Tappen, J.E. Allison, J.A. Hines, R.C. McCune, R.S. Beals, L. Kopka, and P. P. Ried, “The USAMP Magnesium Powertrain Cast Components Project,” 17th Annual Magnesium in Automotive Seminar of the International Magnesium Association, Livonia, MI, April 27, 2006.

4. B.R. Powell, W.L. Miller, L.J. Ouimet, J.A. Hines, R.M. McCune, and J.A. Allison, R.S. Beals, L. Kopka, and P.P. Ried, "The USAMP Magnesium Powertrain Cast Components Project," Proceedings of the Global Powertrain Congress, Novi, Michigan, September 20, 2006.
5. R. Arroyave, M. Ohno, R. Schmidt-Fetzer, and Z.K. Liu, "Finite-Temperature Thermodynamic Properties of Intermetallics in the Mg-Ca-Sn System via First-Principles Methods," Proceedings of the 2006 Magnesium Technology Symposium of TMS, San Antonio, Texas, March 12, 2006, pp. 429-434.
6. B.R. Powell, W.L. Miller, L.J. Ouimet, J.A. Hines, R.M. McCune, J.A. Allison, R.S. Beals, L. Kopka, and P.P. Ried, "The USAMP Magnesium Powertrain Cast Components Project," Proceedings of the 2006 Global Powertrain Congress, ed. Nasim Uddin, Novi, Michigan, 36 pp. 43-50 September 19-21, 2006.
7. R.J. Natkin, B. Oltmans, T.J. Heater, J.E. Allison, J.A. Hines, G.K. Tappen, and D. Peiskammer, "Crank Shaft Support Assembly," Utility Patent Application 11/373,544 filed March 10, 2006.

Acknowledgments

The success of this project is due to the dedicated efforts of a large number of team members at Ford, DaimlerChrysler, and General Motors. The many other companies and organizations making up the project team are listed in Table 1. The continuing support of our respective companies and the US Department of Energy is gratefully acknowledged.

Table 1. The MPCC Project Team.

Product Design:	Ford, GM, DCX, Magna Powertrain
Alloy Suppliers:	AMC, Dead Sea Magnesium, GM, Noranda, Norsk-Hydro, Solikamsk, VSMPO-Avisma
Casters:	Eck, Gibbs, Intermet, Lunt, Meridian, Nematik, Spartan, Thixomat
Bore Treatment:	Gehring, Flame Spray
Tooling:	Becker, Delaware, EXCO, HE Vannatter
Coolants:	Ashland/Valvoline, ChevronTexaco, Honeywell/Prestone, INTAC/CCI
Fasteners:	RIBE
Gaskets:	Dana/Victor Reinz
Testing Labs:	Amalgatech, CANMET, Stork CRL, Quasar, Westmoreland Mechanical Testing & Research
Casting Modeling:	EKK, Flow Science, MAGMASoft, Technalysis
Professional Organizations:	IMA, NADCA
Project Administration :	Ried and Associates

ⁱ Denotes project 304 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.

I. Ultra-Large Castings of Aluminum and Magnesium (AMD 406ⁱ)

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Contractor: United Sates Automotive Materials Partnership

Contract No.: Automotive Metals Division (AMD406) - FC26-02OR22910

Objective

Assess the manufacturing feasibility, economics and mass reduction potential of thin-wall structural castings of aluminum (Al) and magnesium (Mg) applied to automotive weight reduction.

Project Approach

The Ultra-Large Casting (ULC) project builds on the findings of a U.S. Department of Energy funded contract (Project ORNL-12401) to the American Foundry Society (AFS) which benchmarked various casting processes to assess their suitability to manufacture large light-metal castings. Based on this background work and continuing research, the ULC project approach is listed below.

- Further describe and substantiate the rationale for using light-metal castings in place of conventional stamped and welded steel automotive body structures to reduce vehicle weight.
- The project will be executed in two concurrent phases. Phase I is focused on process selection and capability analysis. Phase II is focused on designing, analyzing and testing a "real-world" vehicle application meeting the ULC Team's criteria of an ULC.
- The main objective for *Phase I* is to utilize the selected processes to improve the quality of cast components vs. conventional casting processes by achieving homogeneous distribution of properties and demonstrate consistent and predictable mechanical properties with improved strength and ductility.
- The major tasks for *Phase I* will consist of Flow and Solidification Modeling, Tool Design/Analysis/Fabrication, Correlation with Casting Trials, Material Characterization, Process Capability Studies and an Economic Analysis.
- The main objectives for *Phase II* is a "Real-World" application of an Ultra Large Casting that will demonstrate a mass reduction of 40% - 60% at a competitive cost compared to conventional steel construction. Additionally,

it is desired to demonstrate parts consolidation, reduced investment cost in tooling and dies and improved energy absorption.

- The major tasks supporting *Phase II* are finite-element analyses (FEAs) for Static, Durability, NVH (noise, vibration and hardness) and Crash Analyses; System Level and Full Vehicle Prototype Fabrication; Durability Testing; Dynamic Crash Testing; and an Economic Analysis.

Summary of Previous Accomplishments

- Selected THT Sub-Liquidus Casting (SLC) and Thixomolding for process capability evaluation. SLC focus will be on Al and Mg while Thixomolding is limited to Mg.
- Selected industry participants. COSMA, a division of MAGNA International, through MAGNA's PROMATEK Research Center, will demonstrate the THT SLC process on their 1000-ton THT casting machine. G-MAG, another division of MAGNA, will demonstrate Thixomolding while applying hot-runner technology on a 1000-ton Husky Thixomolding machine. Husky Injection Molding Systems, Ltd. will support G-MAG with access to a 1000-ton machine and necessary hot-runner technology.
- Ford conducted a preliminary cost study which indicates the economics of ULC structural parts are competitive with conventional stamped steel automotive structures.
- A "Test Part" has been designed which embodies the geometric elements and manufacturing challenges that will be encountered in a much larger component. This part will be used to evaluate the capabilities of the SLC process. A "real world" part targeted for potential implementation on a Ford vehicle program will be used to evaluate the capabilities of the Thixomolding process.
- Detailed statements of work were developed with major purchase orders issued to both Promatek and G-MAG to cover test-part design, flow and solidification modeling, tool design and tool construction.
- Flow and solidification modeling of test part is in progress under subcontract to Promatek. Modeling was subcontracted to EKK and Hitachi by G-Mag.
- A design geometry/solid model for the "real-world" part is near completion. Preliminary FEA Studies for Static Crash, Dynamic Crash, and Durability Analyses were completed by Ford.

2006 Accomplishments

Since October 1, 2005 the following has been accomplished:

- Sub-Liquidus Casting Process Evaluation for Test Part
 - Test part design completed.
 - Test part tooling design completed and tool fabricated
 - First iteration of die cavity fabricated
 - Decision made to evaluate Mg in addition to Al with SLC process
 - Design of Experiments developed to streamline evaluation of SLC process
 - Fluidity casting trial underway
- Thixomolding Process Demonstration for production of Ford "Shotguns"
 - Completed construction of thixomold tool for Ford "shotgun"
 - Completed "hot-runner" system critical to demonstrate ultra-large thixocasting capability
 - Completed flow simulations necessary to complete the tool design and guide design of experiment
 - Complete analysis for process optimization
 - Produced shotgun samples of AZ91 and AM60 Mg alloys
 - Successfully demonstrated multi-drop hot-runner technology

- Completed mold refinements based upon initial trials
- Completed equipment modifications for the required larger shot sizes
- X-ray and porosity results of initial AM60 parts are much improved over die-cast parts
- Design of experiments developed.

Future Direction

The ULC Team will continue toward its ultimate goal of demonstrating how light-metal cast body structural parts can provide a 40% to 60% weight reduction at a competitive cost compared to today's conventional stamped steel approaches. The weight reduction is certainly achievable. The key is to have a robust process to produce such parts. The immediate focus of the ULC team is to assess the capabilities of SLC and Thixomolding, which are both semi-solid die-casting processes. Based upon recent successes, both processes will be aggressively pursued through the evaluation. The SLC process has been extended to include evaluation of the casting system operating on AM60 alloy as well as Al A356.2. Should other suitable processes be identified and appear to have potential, the ULC team will consult the AMD¹ Board of Directors to request modifications to the project scope, timing and funding.

Introduction

The rationale for ULCs

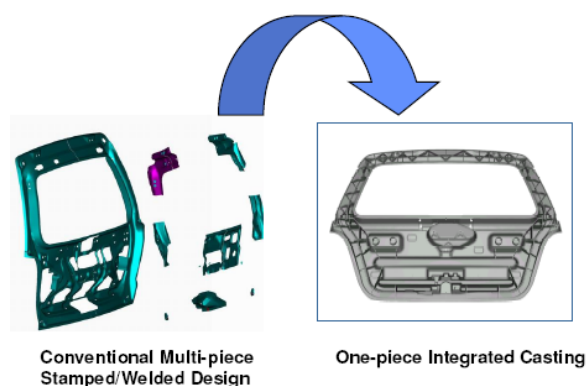


Figure 1

The majority of mass-market automobile and light-truck body structures are constructed of sheet-metal stampings fastened together with resistance spot welding. This method of construction tends to increase the weight of the body because it introduces structural redundancies. For example, an outer panel requires an inner panel for stiffness, which in turn might require local reinforcements. The casting process enables all of these structural elements and features to be integrated into a single piece, and thus has the potential to significantly reduce weight. This logic is illustrated with the example in Figure 1, which shows how a multi-piece stamped steel liftgate inner structure could be integrated into a single casting. There are numerous examples in the industry literature to be cited, however, the basic justification for ULCs is the ability to *reduce cost* by

integrating components and *reduce weight* by taking advantage of the casting process to eliminate structural redundancies and, additionally, using lower-density material such as Mg and Al. Preliminary studies indicate large castings can be cost competitive with conventional stamped steel; however, a comprehensive, definitive case study comparing a true structural casting to conventional multi-piece stamped and welded construction has yet to be completed. Such a case study is essential for substantiating the rationale for ULCs and will be undertaken by the ULC Team.

Existing applications of large light-metal castings.

There are many examples in the industry of what are considered ULCs such as die-cast Mg instrument panel structures, seat structures, closure inner structures, etc. However, it is more appropriate to describe these applications as quasi-structural because they are not totally integrated into the body structure. These quasi-structural components demonstrate the light-weighting potential of large castings replacing conventional stamped steel structures.

A notable example of a truly structural ULC is the current Ford F-150 radiator support structure (Figure 2). It is one-piece, thin-walled Mg casting that replaces seven major stamped steel parts for a 25 lbs. weight savings. It is integrated into the body structure where it contributes to torsional stiffness and plays a role in crash. If applications of structural ULCs like the F150 radiator support and other large

quasi-structural parts already exist, why is there a need for an ULC project? These particular components are manufactured using the conventional high-pressure die casting (HPDC) process, which has some inherent limitations in achieving consistent mechanical properties.



Figure 2

Current manufacturing processes for producing large light metal castings.

The F150 radiator support and most large quasi-structural automotive light-metal castings are manufactured with the HPDC process. While they perform adequately in many applications, HPDCs may not be suitable for other primary structures like pillars, rails or bodysides that have to manage large amounts of crash energy. HPDCs lack the level of ductility and other desirable mechanical properties for these structural applications. Therefore, further uses of HPDCs beyond today's applications are limited by the process capabilities and by the mechanical properties achievable with conventional die-casting.

Utilizing a relatively simple process such as HPDC to make structural parts is highly desirable by the industry. Unfortunately, the presence of porosity in HPDCs has a detrimental effect on mechanical properties. A plethora of countermeasures has been developed to combat porosity (and other shortcomings) of the HPDC process by introducing into the process vacuum, non-turbulent filling of the shot sleeve, and "squeezing" during solidification. There are also expensive, specialty heat-treatable alloys that are used along with one or more of the countermeasures to lower porosity levels. In spite of these enhancements and spin-off HPDC based

processes, HPDCs continue to be plagued by porosity and non-uniform mechanical properties. This inhibits the wide use of HPDCs as primary structural parts.

Besides porosity and non-uniform mechanical properties, adapting HPDC to ULCs presents other challenges such as low yield. In some cases, over 50% of the shot weight consists of biscuits, runners and overflows. This has an effect on economics, especially for Mg diecastings since Mg is not easily recycled in-process. As casting size increases, runner systems become larger and more complex, increasing tooling cost and necessitating the use of larger-tonnage diecasting machines. This significantly increases the cost of capital equipment.

Alternatives to HPDC

An attempt to demonstrate production feasibility of ultra-large, thin-wall, structural castings to achieve weight reduction at competitive costs resulted in a major effort by Alcoa and DOE¹ in the late 1990's. A novel, low-pressure, multiport hot-chamber injection process was pursued and technical difficulties arose relative to the metal-injector system. Alcoa regarded the ULC market to be futuristic and elected not to direct additional funds and resources to address the technical issues. At the end of this three-year effort by Alcoa and DOE, a number of minivan inner panels were cast for evaluation. A panel is shown in Figure 3. This is a single casting that replaces an assembly of 11 stampings. However, DOE, working with the AFS, continued to pursue ULCs. As a result, two documents^{2,3} demonstrating the potential value of ULCs were produced. These studies showed that ultra-large components could be produced at costs competitive with steel structures for vehicles in the range of 70,000 units per year. At the higher volumes, traditional steel stampings become more cost attractive. The primary difference for the volume transition is the lower tooling costs associated with castings versus tooling required for stampings and subsequent assembly.



Figure 3

In addition to an economic impact of ULCs, a complete life-cycle-energy analysis indicated that such structures of Al will ultimately provide an overall reduction in energy required for transportation. A similar analysis for Mg is likely to yield the same conclusion.

The efforts by AFS and DOE identified candidate processes suitable for ULCs and these included:

- a) multiport hot-chamber injection at pressures compatible with typical permanent-mold systems.
- b) single gas plenum driving metal to fill a ULC permanent mold
- c) the Brocast process (France) utilizing gas-driven metal for filling, pressures up to 15 bars, vacuum levels to 50 mbars producing both Mg- and Al-alloy castings
- d) the THT Inc. sub-liquidus casting process, "SLC," to produce Al castings via a semi-solid process
- e) the Thixomolding process to form Mg solids into quality cast components in a semi-solid process without having to handle molten Mg.

Fundamental technical challenges need to be resolved in a) and b) above. Both economic and technical issues are present in the Brocast process (i.e., item c) above). Casting hardware and technology is rapidly emerging for the last two processes shown and these were selected for demonstration of ULC technology.

THT's "SLC" process is a system that's compatible for using multiple injectors. In addition, the process has been shown to produce castings in a T5 temper having properties approaching those requiring a full

solution heat treatment (e.g., T6). It has long been concluded that thin-wall Al ULCs must be used in an "as-cast" condition or a T5 condition. The high costs due to dimensional management (i.e., straightening) associated with the solution heat treatment process must be avoided. Finally, small Mg automotive structural parts are now manufactured utilizing the Thixomolding process. Recently, hot-runner technology has been developed and demonstrated by Husky. The combination of larger available machines (e.g., 1000-ton and greater) coupled with hot runner technology makes the Thixomolding process a very attractive candidate for producing ULCs.

The ULC Project picks up where the AFS/DOE benchmarking left off by seeking to evaluate the potential of SLC and Thixomolding processes to produce ULCs. Both of these processes involve semi-solid metal (SSM) casting. SSM has been practiced across the U.S. for approximately 35 years. Several advantages of the SSM process include:

- product complexity, close dimensional tolerances, near net shape, thin walls and excellent surface finish compared to conventional die castings;
- exceptional soundness, in most cases SSM castings contain less than 0.1% porosity, better than any other mass-production casting process;
- ability to utilize a variety of alloys;
- low process temperature resulting in short cycle times and low stress on tooling;
- ability to undergo a T5 heat treatment without losing ductility. This allows the castings to achieve required mechanical properties without the dangers of blistering, distortion or quench stress associated with the full T6 heat treatment required of other structural casting processes.

The SLC Process

The SLC process is the latest approach to SSM casting, developed by THT Presses, Inc., Dayton, Ohio. The SLC process uses normal foundry ingot, primary or secondary, and requires no processing equipment extraneous to the casting machine or processing time outside of the normal diecasting cycle. SLC is suitable for casting both Al and Mg.

The SLC machines (Figure 4) have a vertical shot and a horizontal die-parting configuration. While the machine is somewhat smaller, it offers an equivalent shot capability of a larger, more conventional machine. Also, because of their unique shot-sleeve and piston design, the machines are capable of larger shots than machines of higher tonnage.

The SLC process employs a large-diameter, short-stroke approach. This feature allows for larger shots and enables tight control of the metal temperature required for SSM slurry processing. This reduces plunger speed necessity, drastically reducing impact pressures at the conclusion of each shot. This also provides the opportunity for multiple-cavity gating.

Some THT machines incorporate an indexing table feature which enables pouring molten metal into a shot tube at one station, making appropriate temperature adjustments and achieving required slurry ripening, then making the actual shot in the next shot tube and removing the biscuit in the last station. Unlike other SSM slurry approaches, the SLC process requires virtually no slug-pre-preparation equipment or processing time outside of the casting machine.

The SLC shot-sleeve design (depicted in Figure 5) naturally provides both the time necessary in the semi-solid temperature regime to gain the globular structure desired and a major portion of the poured shot suitable to enter the die cavity (more than 60%). This all can occur within the normal machine cycle.

Suitable SSM structures can be achieved in the SLC process. Mechanical properties achieved in castings from those slurries are comparable to and sometimes higher than those realized from magnetohydrodynamically (MHD)-stirred, billet-based SSM castings.

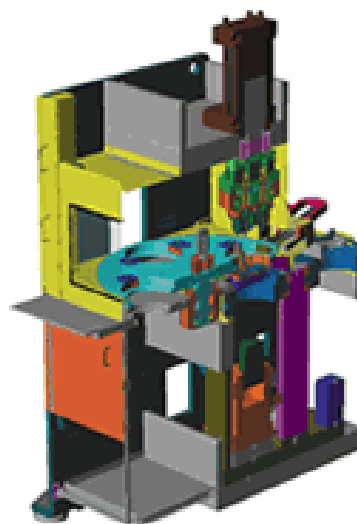


Figure 4. THT SLC casting machine.

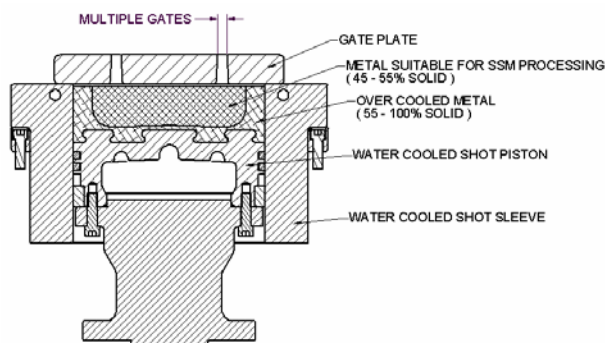


Figure 5. SLC shot sleeve.

The Thixomolding Process

A second SSM casting variation is the Thixomolding process, which offers higher-ductility Mg castings with high strength and low wall thickness. Thixomolding combines conventional diecasting and plastic injection molding into a one-step process for the net-shape molding of Mg alloys.

The process requires no investment in molten-metal process and handling equipment, eliminating the safety hazards of handling molten Mg. The injection system, which is similar to plastic injection molding machines, consists of a high-temperature screw and barrel coupled to a high-speed shot system that drives the reciprocating screw.

In the process (Figure 6), Mg-alloy feedstock is thermally processed by the rotating screw and then injected into a die cavity. The temperature is then raised to a semi-solid region and, after determining the desired temperature and shot size, is injected into a preheated metal mold. The screw is driven forward, filling the die cavity. The small amount of turbulence allows thixomolded components to have low levels of porosity and gives designers dimensional stability with precision and repeatability. Also, since the process does not require any external foundry or material handling, it is considered environmentally friendly.

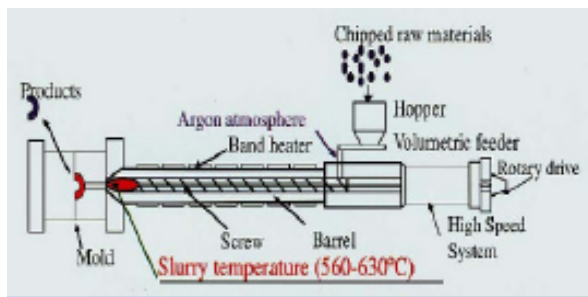


Figure 6. Thixomolding schematic.

Process Evaluation-“SLC”

The key component of Phase I is development of a test part that presents the fundamental challenges of an ultra-large, thin-wall casting and requires inexpensive tooling but produces **key process understanding**. After a number of meetings and discussions, the “test part” shown in Figure 7 resulted. This part includes options to gate at one, two, three or four locations. It enables flow lengths as great as 48” before forming knit lines. This gating provides significant flexibility in the testing. In addition, typical features characteristic of a structural component are included (e.g., ribs, steps, round bosses, “D” bosses, “C” channels, and “X” bracing). The target for nominal thickness is 2 mm, but it is realized that this may need to be increased to as much as 3 mm for production of quality castings.

Simpler casting fluidity trials utilizing a constant thickness (2 to 3 mm) with uniform width will be the first action step in Phase I. The flow path will follow the same outline as the “test part”. Following

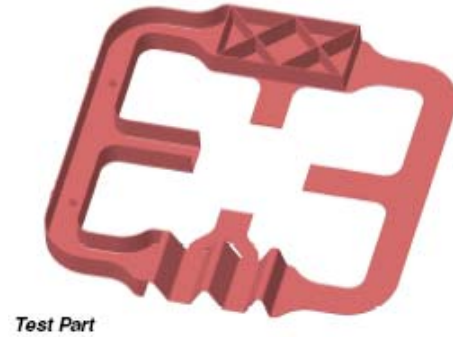


Figure 7. Test part geometry.

the fluidity trials, a materials characterization will be conducted prior to casting the test parts. The fluidity trial will provide the first comparison between computer process simulation and the actual results. Based upon these results, the part nominal thickness will be selected and the test-part design finalized. The materials characterization will involve casting of components to assess mechanical and corrosion properties. Properties will include:

- a) Tensile
- b) Compression
- c) Poisson’s ratio
- d) Modulus
- e) Low-cycle fatigue
- f) Microstructural examination
- g) Toughness (K_{IC} and da/dN)

A much smaller number of these tests will be utilized to adjust the process in an attempt to optimize process conditions. For example, the conditions for part removal and quench will be evaluated with respect to mechanical properties. During the materials characterization, a ring geometry will be produced that clearly produces a knit line. A test will be conducted to evaluate the quality of the knit line. In cases of failure, the fracture region will be evaluated relative to oxide content and general cause of knit-line failure.

Finally, approximately 20 to 25 castings will be selected at random during the production of over 200 cast test parts. Approximately 8 locations will be selected for tensile, yield, and elongation (TYE) evaluation in addition to conducting some microstructural analyses in at least two key areas of the casting. The Phase I effort evaluating only the “SLC” process will be conducted on the 1000-ton

THT machine that was installed in late 2004 and now fully operational at the Promatek Research Center (Brampton, Ontario).

A fluidity test part (see casting in Figure 8) measuring approximately 16 in. x 16 in. provides a maximum flow length exceeding 48 inches.

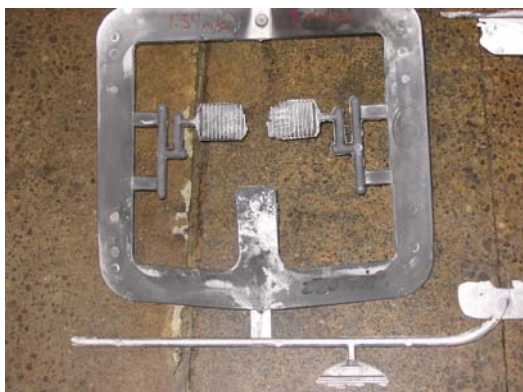


Figure 8. Fluidity test part 2.5-mm-thick A356.2.

The test-part geometry will be used to evaluate the SLC process using A356.2 Al alloy and AM60 Mg alloy. These tests are currently underway at Promatek began in July with completion of all tests expected by 2nd Quarter of 2007.

Evaluation of the Thixomolding process is considered much more mature than SLC and will focus directly on the “real-world” vehicle cast part (see below). Materials characterization will be based upon excised specimens from the cast parts.

"Real-World" Vehicle Application

It is important to demonstrate that the process knowledge gained can be applied to real-world vehicle lightweighting. The demonstration chosen by the ULC team is to replace the conventional multi-piece steel structure that forms the inner front fender—known in the industry as a “shotgun”—with a single casting. The “shotgun” structurally joins the A-pillar to the radiator support structure on Ford light trucks. The simulation of the part filling at four drops via hot-runner technology is shown in Figure 9. Depicted in Figure 10 is the “shotgun” (42 inch length) for the passenger side with the attachment to the radiator support at the right and

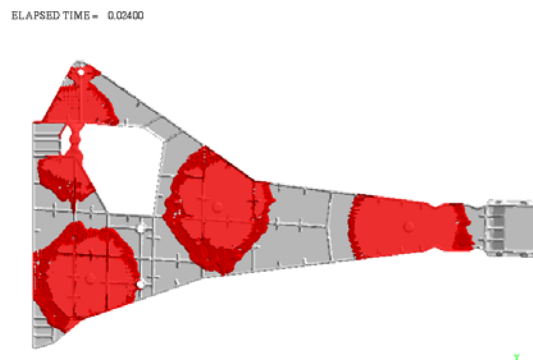


Figure 9. Snapshot of flow simulation and filling pattern for 4-drop hot runner.



Figure 10. Thixocast AM60 “shotgun.”

A-pillar attachment to the left. This was produced in AM60 Mg alloy.

To demonstrate ULC process capability, it was necessary to develop and demonstrate the use of hot runners with multiple drops in producing this part.

This was successfully done initially with AZ91 Mg alloy and now is being done in AM60. Numerous parts have been examined by x-ray and found to be of high quality. In these first set of AM60 parts, porosity was found to be less than 2% in critical areas with other locations as high as 6%. Parts are currently undergoing TYE evaluation before moving forward with the design of experiments.

Following the design-of-experiment evaluation, parts will be produced in sufficient quantities to a) evaluate the variability of part quality b) evaluate the parts in full component tests and c) do full vehicle testing.

While this particular component would not necessarily be considered “ultra-large,” it embodies the geometric elements and manufacturing

challenges that might be encountered in a much larger component, such as an entire bodyside. The shotgun application is of further interest to researchers because it is integrated into the body structure (Figure 11) where it contributes to stiffness (which has durability and NVH implications) and plays a role in conducting and absorbing crash energy (Figure 12).

Furthermore, the shotguns will attach to a radiator support that *is* an ULC in its own right. The end result of this study will be a front-end structure for large body-on-frame pickup or sport utility vehicle (SUV) (Figure 13) constructed entirely of castings demonstrating a weight savings of 50% to 60 % compared to conventional steel architectures.



Figure 11. Shotgun will be integrated with the body structure.



Figure 12. Shotgun must manage crash energy.



Figure 13. A demonstration front-end structure consisting entirely of large castings will replace conventional steel construction.

Conclusions

The ULC project has made good progress since October 2005. Building on the foundation laid in the joint AFS/DOE benchmarking study, the ULC team has identified two emerging casting processes, Sub-Liquidus Casting and Thixomolding with Multiple Hot Runners, which have the potential to produce low-cost large castings with mechanical properties much better than those achievable with high-pressure die casting (the industry's preferred process). In addition to the fundamental research required to evaluate these emerging casting processes, the Team has developed a real-world automotive application that is targeted for potential implementation on an OEM vehicle program. In fiscal year 2007, the team expects to continue to assess the capabilities of SLC and Thixomolding by analyzing parts produced by both processes.

The largest structural part ever produced by thixomolding exhibits the potential to yield part quality far exceeding that of conventional die casting.

The initial results of "SLC" demonstrate metal flow lengths exceeding 24" while maintaining low flow velocity for quality 2.5-mm-thick parts (i.e., A356.2 alloy). As a result, successful results are expected for the 2.0-mm-thick part. Although "SLC" tests with AM60 have just begun, it is anticipated that casting ability will further improve over that achieved with Al.

Presentations and Publications

No publications or presentations have been made at this time.

References

1. Final Report, Subcontract No. 86X-SU545C, “Development of a Casting Process for Ultra-Large Automotive Components,” April 28, 2000.
2. AFS Project ORNL-ULC, July 16, 2002.
3. AFS Project ORNL-ULC-II, July 30, 2003.
4. “Sub Liquidus Casting (SLC): Process, Concept and Product,” J. Jorstad, M. Thieman, R. Kamm, M. Loughman and T. Woehlke, 2003 AFS Transactions, No. 03-162.

ⁱ Denotes project 406 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.

J. High Integrity Magnesium Automotive Castings (HI-MAC, AMD 601ⁱ)

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*Contractor: U.S. Automotive Materials Partnership AMD 601
Contract No.: FC26-02OR22910*

Objective

Develop and validate casting process technologies needed to manufacture squeeze-cast and low-pressure-cast magnesium (Mg) automotive suspension components. Address critical technology barriers inhibiting Mg application and component affordability. Deliver components for static and/or vehicle testing. Evaluate potential of emerging casting technologies.

Approach

Casting Process Development: Broaden the range for potential cast Mg-component applications by developing casting technologies for production of automotive suspension and powertrain components with a greater range of geometries and properties than are available today. Evaluate “Ablation” and other new casting processes for the casting of Mg automotive components.

Development of Enabling Technologies and Material Science:

Address key technology barriers that currently limit the casting of Mg automobile suspension and chassis applications and affect the cost of cast Mg components. Specific technologies include: computer modeling to enable prediction of casting quality and microstructure; thermal treatment including research into stepped heat treatment and fluidized beds; microstructure control during casting including grain refining; fatigue performance testing.

Accomplishments

This project was approved on April 1, 2006, and since that time the project team has:

- Held two quarterly review meetings for the 46 project participants including: (Universities (6); National Laboratory (1); manufacturing and industrial companies (39).
- Established eight steering committees to work on each of the major project tasks.
- Retrofitted and “ready to dry-run test” one squeeze-cast machine in support of Task #1 (Figure 1).



Figure 1. Squeeze-cast machine retrofitted and ready to dry-run test.

- Met all projected guidelines for the issuance of purchase orders and the collection of project in-kind.
- Preliminary results from the Mg core gas studies at the University of Alabama at Birmingham (UAB) have been received. The studies demonstrated significantly higher core gas evolution when cores are in contact with molten Mg than when in contact with aluminum (Al). Additional work is continuing including the analyses of gas by-products generated.
- A work team has been organized to coordinate Low-pressure Permanent Mold (LPPM) Task 2 and Metal Filling Task 6. Several group meetings were held to transfer technology within group and define technical goals. The team has completed the design and engineering of major components including: Mg LPPM Equipment; one furnace system; metal-transfer system from the melting furnace to casting furnace; cover-gas management and recirculation system; mold hot-oil-heating system; the proposed Casting Component (control arm) has been designed for Mg and initial modeling completed; combined team meeting with LPPM group to discuss strategies to combine metal pump with LPPM equipment in future casting trails; conducted a literature review to determine history of liquid Mg pumping and capabilities of various pumps designs (see Figure 2).
- Completed eight project presentations at CANMET's technical meeting in October, 2006. No publications have been presented at this time in support of the HI-MAC project.

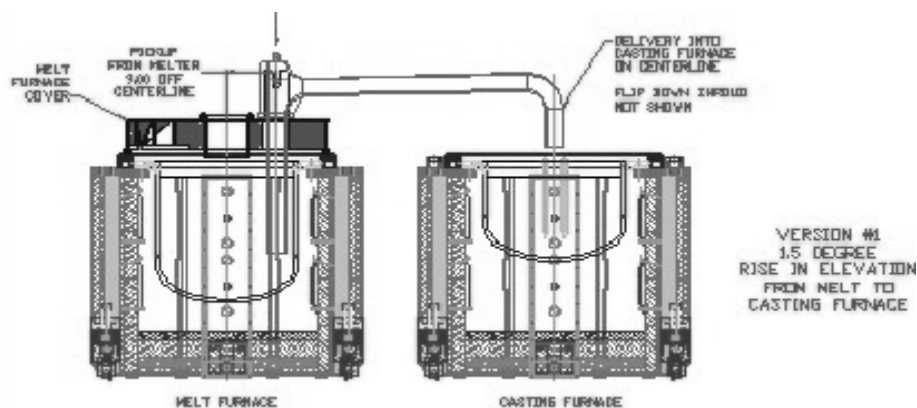


Figure 2. The dual furnace system for the LPPM casting equipment includes a casting furnace (that will sit under the LPPM machine), and a separate melting furnace to provide easy access for melt control and protection. A pressurized pump will transfer metal from the melting furnace into the casting furnace. (Proposed engineering drawings may be modified prior to final build).

Future Direction

- The project team will follow the Statement of Work and the respective time line for each of the eight tasks.
- With in the next year, it is expected that the following items will be completed:
 - The design and completion of the Low Pressure Mg Casting machine and the squeeze-cast machine will be completed and test samples run.
 - The metal transfer pump design will be completed, and a new pump will be built. Initially, molten Zn will be tested prior to the testing of Mg.
 - Computer modeling companies have been defined in support of the project deliverables, and their progress will be tracked in accordance with the project's SOW.

Introduction

The use of Mg automotive components in new-vehicle applications can be utilized to reduce vehicle weight and improve performance. Mg sheet and wrought technologies hold potential for vehicle application, but application is long-term. Perhaps the quickest near-term path to increased Mg content in automobiles is through increased use of metal castings.

Wider vehicle application of cast Mg components offers a potential weight reduction of nearly 100 kg per vehicle. The Structural Cast Magnesium Development (SCMD) project (see 2.G) has successfully demonstrated the re-design, conversion, and production of a production cast aluminum (Al) engine cradle to cast Mg, providing weight reduction of approximately 35%. Similar applications of Mg castings for suspension and chassis components can be achieved. To produce affordable, high-strength Mg castings, it will be necessary to develop and

optimize Mg-casting procedures (existing and/or new) and to develop tools that support the casting process and reduce the cost of Mg components.

The USAMP *Magnesium Vision 2020* document (see 2.G) identifies the cost and quality of Mg components, the need for engineering and manufacturing process development and the lack of enabling infrastructure as key inhibitors to cast-Mg applications on vehicles. Specifically, the document vision identifies three key technology barriers that must be overcome to increase the application of Mg cast components in vehicles by 2020:

- Lower manufacturing costs
- Improved casting quality requiring lower porosity and new casting methods
- Infrastructure development

The High Integrity Magnesium Automotive Casting (HI-MAC) project addresses the near- and mid-term

metal-casting development needs identified in the *Magnesium Vision 2020* document. Eliminating these technical barriers that currently inhibit Mg-casting production will move the automotive industry into a better position to realize emerging automotive Mg-component needs, build needed Mg-industry infrastructure and develop tools that will be needed to reduce the cost of Mg components and enable sustainable production requirements. The HI-MAC project will address these three key issues:

- **Development of Casting Tools:** Develop technologies and tools that will be required for sustainable long-term procurement of cast-Mg automotive components (Tasks 3, 4, 5 and 6). These tasks will address the science and technological barriers that currently inhibit production and affect the affordability of cast-Mg components.
- **Casting Process Development:** Develop casting processes to facilitate production of cast-Mg automotive chassis components that cannot be manufactured using current process limits (Tasks 1, 2 and 7).
- **Infrastructure Development:** Development of casting processes and tools will include industry participation by automotive suppliers currently producing Al components (Tasks 1, 2, 7), the development of equipment uniquely suitable for the production of Mg components (Task 2, 6) and development of a broader research and science base (Tasks 3, 4, 5, 8).

Research teams associated with the HI-MAC project will broaden the range for potential cast-Mg component applications by developing and optimizing manufacturing technologies that can produce a greater range of geometries and properties than are available today and encourage potential supplier-base infrastructure through project partnerships. Additionally, HI-MAC will investigate and evaluate new and emerging technologies and develop tools that address critical technology barriers currently inhibiting Mg application and component affordability. Technical challenges are identified for each task.

Casting process and tool development will be demonstrated by production of a Mg control arm by low-pressure-cast, squeeze-cast and a new emerging

casting process. Control arms will be delivered for static and/or vehicle testing.

The project is divided into seven tasks to address key technology barriers that limit cast-Mg automobile suspension and chassis applications and affect the manufacturing costs of these components.

Task 1: Squeeze-casting process development

Task 2: Low-pressure casting process development

Task 3: Thermal treatment of castings including research into stepped heat treatment and fluidized beds

Task 4: Microstructure control during casting including grain refining and property improvement

Task 5: Computer modeling and properties to enable prediction of casting quality and microstructure

Task 6: Controlled Molten Metal Transfer and Filling

Task 7: Emerging Casting Technologies

Task 8: Technology Transfer

Conclusions

The development of squeeze- and low- pressure casting processes for Mg automotive components will enable production of Mg suspension castings with property requirements and geometries not currently feasible with high-pressure die casting. Enabling technologies will reduce processing costs of Mg components.

ⁱ Denotes project 601 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership, one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.

K. Magnesium Front End (AMD 603ⁱ and AMD 604ⁱ)

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Contract No.: FC26-02OR22910

Objective

The Magnesium Front End (MFE) effort consists of the two related projects:

- **Magnesium Front End Design and Development (AMD 603)**: The goal of this USAMP project is to develop and validate lightweight magnesium (Mg) front end designs for unibody and body-on-frame architectures with 50-60% mass reduction and equivalent performance compared to the steel baseline.
- **Magnesium Front End Research and Development (AMD604)**: The goal of this Canada-China-US collaborative project is to develop key enabling technologies (e.g., high-integrity body castings, extrusions, sheet forming, joining) and the accompanying knowledge base (crashworthiness, NVH, durability and corrosion resistance) to permit design, and eventual implementation of lightweight Mg automotive body structures with equivalent performance and affordable cost.

Two attributes of this effort are particularly significant:

- The focus on an entire “front end” structures as the development object as opposed to individual components, thereby offering critical vehicle-level benefits in terms of mass distribution and performance, while challenging the technical community to devise materials and manufacturing approaches to permit mass production of such structures.
- The establishment of a truly international effort (AMD 604) bringing together scientific and engineering expertise in the field of Mg technology from Canada, China and the United States, in what may be a first-of-its-kind collaboration.

Approach

- **Project Organization and Administration**. Because of the magnitude of the overall effort involving both fundamentally new and challenging technologies, and also a high level of international collaboration and participation, particular attention has been paid to the establishment of an organizational and management structure that facilitates both the flow of information and the coordination of activities.

- Partitioning of Projects. The extent of this effort also demands careful partitioning of the technical tasks, firstly, at the international level by degree of alignment and capabilities directed toward the overall goals, and, secondly, on a technical level which separates the design and analysis function from the enabling technologies required to achieve the intended outcomes.
- Design and Analysis. The design and analysis functions relating to the envisioned Mg front-end structures are partitioned under a separate USAMP project (AMD 603 Magnesium Front End Design and Development – MFEDD) for purposes of retaining OEM-critical design aspects within the confines of the USCAR collaboration agreement between Ford, GM and DaimlerChrysler. “Donor” design target vehicle structures have been provided by GM (rear-wheel-drive (RWD) unibody design) and Ford (light truck body-on-frame (BOF)). These structural “envelopes” will serve as the starting point for consideration of material replacement with Mg alloys. Actual designs employable in computer-aided engineering (CAE) and subsequent analysis are expected to be conducted by an independent design house.
- Enabling Technologies. The ability to actually fabricate a Mg-intensive front-end structure for use in mass-produced automobiles critically depends on existence and implementation of robust technologies for manufacturing and, furthermore, material properties that provide acceptable, if not superior, performance to their present comparators (in this case principally steel stampings joined by resistance welding, arc welding or adhesive bonding). It is the area of “enabling technologies” that is expected to achieve the greatest benefit from international collaboration with experts in metal production, forming, joining, finishing and durability. This aspect is the basis for the Magnesium Front End Research and Development (MFERD) project, AMD 604.
- Integrated Computational Materials Engineering (ICME). This is the third, related USAMP project, which is critical to the automotive applications of Mg alloys and other materials. ICME is intended to provide a unifying organization structure to a palette of computational tools integrating materials engineering and manufacturing disciplines.
- Technical Gateways. As in most product development formalisms, technical gateways provide the means for assessing engineering progress against intended metrics at sub-levels of the project, with the aim of assuring overall targets are ultimately achieved, or, alternatively, that further work is discontinued if required metrics cannot be achieved. In this effort, gateways exist for both the design stage and also for the enabling technologies, such that efforts for actual prototype build (Phase 2) only occur at successful accomplishment of Phase 1. Overall timing and conceptual flow is illustrated in Figure 1.

Accomplishments

- Official launch of AMD 603 and AMD 604 occurred with the OEM “kickoff” meeting on November 1, 2006 at USCAR Headquarters, followed by an OEM-Supplier kickoff on November 28. Following the November, 2006 kickoff meetings, the individual project task teams in AMD 603 and AMD 604 have begun organizational meetings, participant selection and refinement of the various technical agendas. These activities are expected to continue into 2007 as both the USAMP and international technical formats evolve.
- Leading up to launch of the MFERD project by the respective organizations in the Canada, China and U.S., was an over three-year effort in the organization and management structure tasks by representatives of DOE, USAMP, CANMET, the Chinese Ministry of Science and Technology (MOST), the China Nonferrous Metals Industry Technical Development and Exchange Center, and individual researchers, primarily the following events:
 1. Informal discussion of the concept of a three-way international collaboration by Dr. Joseph Carpenter (U.S. DOE), Dr. Jennifer Jackman (CANMET) and Professors Shoumei Xiong and Baicheng Liu of Tsinghua University (Beijing) at the Light Metals Technology Conference in Brisbane, Queensland, Australia in September, 2003.
 2. More extensive discussion involving Drs. Carpenter and Jackman and Chinese Ministry of Science and Technology (MOST) officials (Mr. Bing Liu, Mr. Jing Xu) and Dr. Wenfang Shi (China Nonferrous Metals Industry Technical Development and Exchange Center) at the International Magnesium Conference (Beijing, September 2004). Subsequent discussions at this meeting also included Dr. Alan Luo of General Motors Corporation.

3. A technical organizing meeting held at the campus of the University of Michigan – Dearborn in October of 2005, at which time the conceptual target of the vehicle front end structure was introduced by Dr. Luo as a “focal point” for collaborative work between the three nations.
 4. Meetings of the ad hoc Project Steering Committee (PSC) and Project Technical Committee (PTC) at Kauai, Hawaii in April, 2006 and Beijing in June of 2006, further defining the management structure and operating principles.
- By the end of calendar 2006, all three participating countries had conducted project kick-off events for MFERD, and the technical teams had begun organization and refinement of the technical agenda set forth in the project statement of work (SOW) which had been agreed to during 2006.

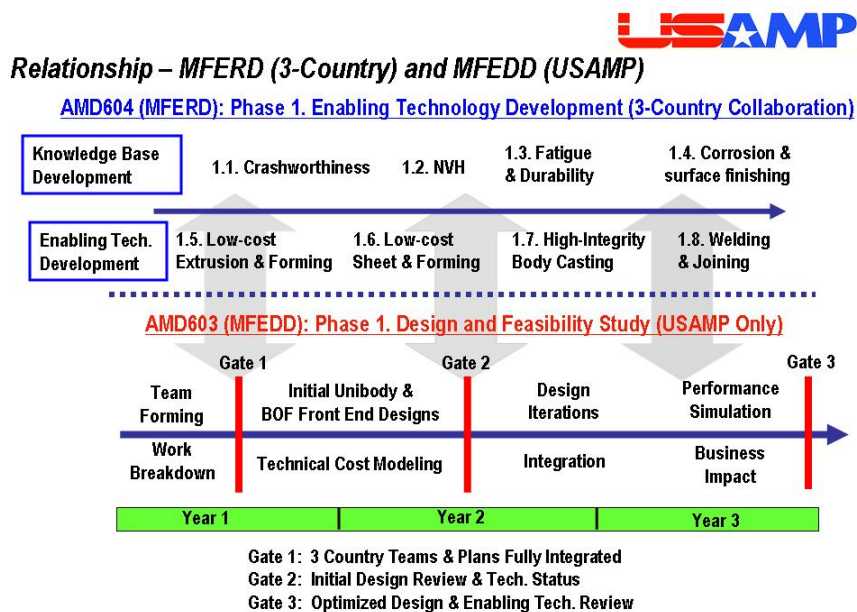


Figure 1. Structure and timing of Magnesium Front End effort.

Future Direction

- The AMD 603 design and analysis task will start in the first quarter, and the technical cost modeling task will begin in the fourth quarter in 2007.
- The next official event for AMD 604 will be meetings of the Project Steering Committee (PSC), Project Technical Committee (PTC) and individual task areas on March 1 and 2, 2007, following the TMS Annual Meeting in Orlando, FL, that week. A collaborative R&D work plan is expected to be prepared and agreed by all country task leaders, for each task, at this event. Ongoing events for the visiting Chinese participants are planned for the Detroit area the following week.
- It is expected that the ICME project will be approved by USAMP and funded by DOE in 2007. Using the Mg front-end body application as a test bed, this project aims to establish an ICME infrastructure for alloy development, microstructural engineering, and process and product optimization.

Mg Front End Development Activities

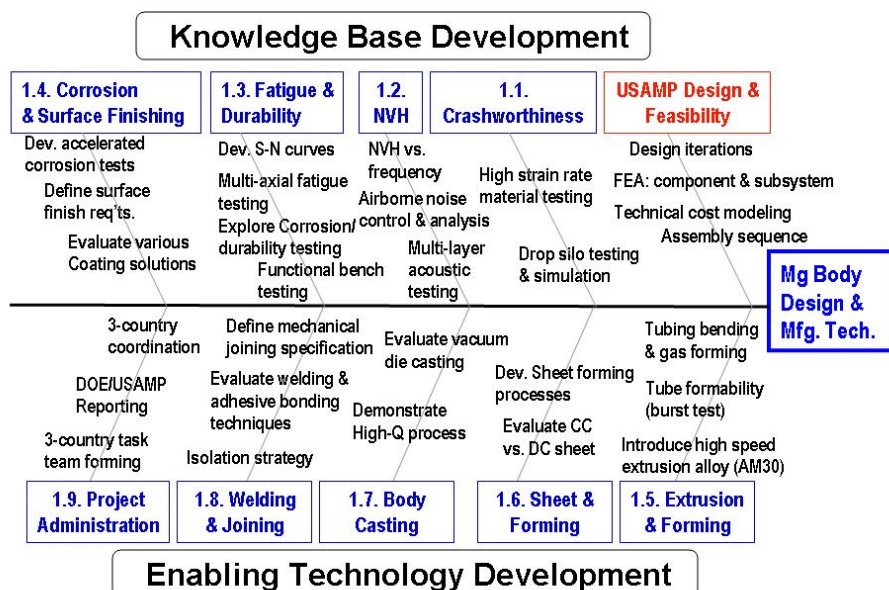


Figure 2. Magnesium Front End Research and Development project structure fishbone diagram.

Introduction

Despite both advances in Mg manufacturing technologies and favorable material costs leading to generally increasing levels of use in automotive structures, widespread and expansive use of Mg alloys as a major automotive structural material in the same class as steel and aluminum (Al) is yet to be realized. This is, in part, due to fundamental physical properties of Mg castings, which are the predominant form of usage, particularly with regard to deformation and fracture behaviors. Furthermore, technologies which permit the manufacture of extended structures by joining of individually formed components are not well-developed for this material. Nevertheless, as a structural material, with high strength-to-weight values approaching or exceeding that of Al, Mg offers an attractive approach for achieving the FreedomCAR materials goals of up to 50% weight reduction in comparison to steel alternatives, with cost, reliability and recyclability attributes that are comparable or better than other structural materials of consideration for these tasks.

Project AMD 604 (Magnesium Front End Research and Development – MFERD) brings together a unique team of international scope – i.e., Canada,

China and the United States – to explore certain “enabling” technologies which could, if successful, permit the integration of Mg-based subsystems into optimized assemblies for vehicle body structure applications using the “front end” structures as a test bed, thereby permitting exceptional levels of overall vehicle weight reduction and handling attributes supporting the FreedomCAR initiative.

The organizational aspects of the project have been treated in the earlier section of the report and will not be elaborated upon here. The formation of an international effort is aimed at bringing together the unique attributes from each nation, e.g., United States – product development, design and manufacturing, Canada – extractive metallurgy and manufacturing, and China – low-cost extraction, forming and manufacturing, into a homologous project with the common technical focus of a useful and critical aspect of lightweight vehicle architecture.

The following sections describe key technical attributes of the project and accomplishments occurring during FY 2006.

Project Technical Structure and Achievements

Figure 2 illustrates in “fishbone” format, how the various organizational aspects of the project contribute to the overall objective of a durable, affordable and manufacturable magnesium front-end structure. The program is divided into two major elements:

- (1) Knowledge-base development incorporating features of: corrosion resistance and surface treatment (Task 1.4), fatigue and durability (Task 1.3), NVH (Task 1.2) and crashworthiness (Task 1.1), and
- (2) Enabling technologies development including: extrusion and forming (Task 1.5), sheet manufacture and forming (Task 1.6), body castings (Task 1.7), and joining (Task 1.8). Additionally, Task 1.9 provides for a project administrator to assist in matters of project organization, three-country coordination, reporting and financial analysis.

The “fishbone” diagram also illustrates the relationship to a separate but closely related project (AMD 603 - MFEDD) which concentrates on design aspects using contributed design data from the USCAR participant companies (i.e., Ford, DaimlerChrysler and GM), and is organizationally isolated from the three-country collaboration for proprietary reasons.

During 2006, the two “donor” structural platforms, namely, a “unibody” structure for use with an RWD GM vehicle (steel baseline design in Figure 3) and a BOF structure intended for use in a Ford light truck structure (schematized in Figure 4) were identified and formed the basis for future designs and analyses.

In addition to formulating the overall project SOW in FY 2006, project task teams in the U.S. conducted individual organizational meetings for the purpose of identifying potential suppliers and university researchers, as well as refinement of the specific task objectives as will integrate into the overall structure of the effort.

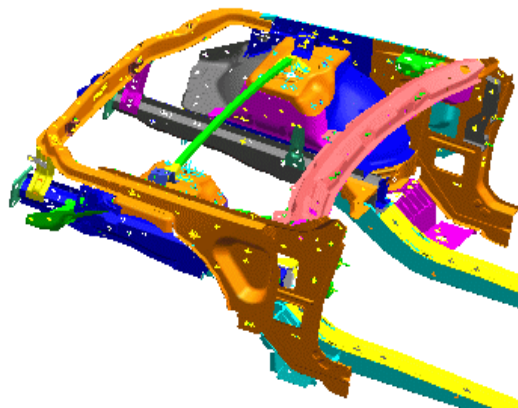


Figure 3. Steel baseline front-end design for unibody architecture.

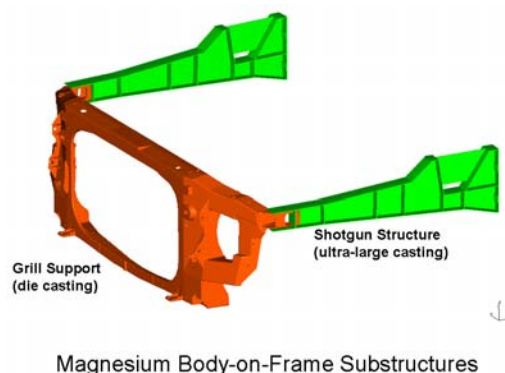


Figure 4. Anticipated elements of magnesium-intensive Body-on-Frame structure.

Conclusions

The Magnesium Front End effort, consisting of the USAMP Magnesium Front End Design and Development (AMD 603) and the first-of-its-kind Canada-China-US collaborative project Magnesium Front End Research and Development (AMD 604), has been formalized and launched in 2006. This project seeks to both explore emerging technologies and conduct basic research in the design, manufacture and performance of structures predicated on forming, joining and finishing of commercial Mg alloys.

Presentations/Publications

- J. Carpenter, J. Jackman, N. Li, R. Osborne, B. Powell, and P. Sklad, “Automotive Magnesium Research and Development in North America,” International Magnesium Association 63rd Annual World Magnesium Conference, Beijing, China, May 21-24, 2006. Plenary

presentation at 2nd International Conference on Magnesium, Beijing, China, June 26-28, 2006.

- A.A. Luo, “Research and Development Challenges for Magnesium Applications in Automotive Structures”, Plenary presentation at 2nd International Conference on Magnesium, Beijing, China, June 26-28, 2006.
- J. Jackman and J. Carpenter, “Automotive Magnesium Research and Development in North America,” Plenary presentation by E. Nyberg at the Intl. Conference on Mg Alloys and their Applications, Dresden, Germany, November 6, 2006.

Acknowledgments

The success of this project is due to the dedicated efforts of a large number of team members at Ford, DaimlerChrysler, and General Motors, as well as international counterparts in Canada and China. The continuing support of our respective organizations and the US Department of Energy is gratefully acknowledged.

ⁱ Denotes projects 603 and 604 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.

L. Magnesium Research and Technology Development

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Contract No.: DE-AC06-76RL01830

Objective

- Support the USAMP's Magnesium Front End Research and Development (MFERD) project in collaboration with China and Canada (See 2.K).
- Compile, document and evaluate state-of-the-art R&D in magnesium (Mg) research around the world as a resource to best determine where U.S. government resources should be directed.

Approach

- Serve as the MFERD U.S. Project Technical Committee (PTC) Chairman, advising the U.S. Project Steering Committee (PSC) member of on-going activities by the PTC and project tasks.
- Assist in the coordination of U.S. MFERD project meetings and joint three-country meetings held in the U.S.
- Evaluate proposals and oversee the effectiveness of the nine tasks of the MFERD project.
- Develop an accessible resource that is available from automotive casting suppliers.

Accomplishments

- Attended the first Canada-China-US Workshop on Automotive Magnesium (Dearborn, MI 10/17-19/05) that established the basis for forming the MFERD project
- Attended the first PSC/PTC working meeting (Kauai, HI, April 2007) where the three-country statement of work (SOW) was developed.
- Participated, by teleconference, in the second PSC/PTC working meeting (Beijing, June 2006) where the SOW was refined, project management and organization guidelines were established, and a timeline was defined.
- Participated in the U.S. MFERD kick-off meeting, introducing the tasks leaders and rolling out work scope to potential U.S. project participants (Detroit, MI November 28, 2006).
- Participated, by teleconference, in the first two PTC meetings (Aug. 24 and Dec. 14, 2006). The purpose of these meetings is to summarize project status for the PSC and to organize future project task meetings.
- Completed the development of the 'Sharepoint' website listing papers written on a variety of Mg research topics from around the world. The site lists titles, authors, contact location and where the information was presented/published. Information is added to the site as it becomes available.

Future Direction

- Primary responsibility for organizing the logistics at the first joint Task Leaders meeting, held in conjunction with the next PSC/PTC meeting (Orlando, FL March 1-2, 2007). Meetings follow the TMS Annual conference.

Introduction

This primary purpose of this project is to support the Canada-China-U.S. collaborative project entitled “Magnesium Front End Research and Development” (MFERD. See 2.K). The goal of the MFERD project is to develop key enabling technologies for a lightweight Mg front-end body structure and other body applications. The MFERD project will develop enabling technologies in high-integrity casting, wrought Mg processing, Mg and dissimilar metal joining and corrosion, and generate scientific understanding in corrosion science, crash-energy management, fatigue, and NVH (noise, vibration and harshness) performance. The project will also provide a platform for Mg research collaboration in Canada, China, and the United States.

Background

The primary goal of the MFERD project is to develop key enabling technologies (body casting, extrusion, sheet & joining) and knowledge base (crashworthiness, NVH, durability, and corrosion) for primary (load-path) body applications of Mg alloys. The following are some specific objectives:

- Define materials and develop manufacturing processes for Mg body castings, extrusions, sheet, and joining technologies.
- Develop knowledge base and define Mg body technical requirements in crashworthiness, NVH, durability, corrosion, and surface finishing.
- Enhance the infrastructure for integrated computational materials engineering for Mg applications, including alloy design/development, process optimization, and component manufacturing.
- A total life-cycle analysis showing the net benefit of vehicle lightweighting, using Mg vs. energy consumption, emission, and pollution in Mg production.
- High-quality professionals and students educated in materials science, engineering, and Mg research and development (R&D)

infrastructure in Canada, China, and the United States.

- Establish automotive OEM / supplier / academia collaboration in Mg body applications.

PNNL Approach to Supporting MFERD Project and Database Development

As the U.S. Project Technical Committee Chairman, I have participated in all project-related meetings since the initial three-country meeting held in Dearborn, MI in October 2005. The continuity and background developed because of this participation has made me uniquely qualified to advise the U.S. Project Steering Committee representative (Dr. Joseph A. Carpenter, Jr.) on the technical issues, task status, and cultural complexities that can, and will develop, as the project matures.

Currently, we are in the midst of organizing the details for the U.S.-hosted Task Leaders’ meeting that will be held in Orlando, Florida on March 2nd, 2007. This meeting will follow the joint PSC/PTC meeting on March 1st and is the first opportunity for the task leaders from each country to meet together. We are organizing all aspects of the facility/meeting arrangements.

We have also completed the Mg R&D database of international research. This is a searchable Sharepoint website that is ready for public deployment upon approval of the DOE Technology Area Development Manager.

Conclusions

This technical-support project is aimed at effectively assisting in the management of the U.S. portion of the three-country MFERD project. To date, we have completed the SOW, Terms of Reference, and assigned the management, advisory and technical task leader positions for the MFERD project.

Additionally, this project will serve as a resource for future funding decisions related to DOE-funded Mg projects.

Future Work

Future work will be to evaluate progress of the tasks, participate in committee meetings, report results and make recommendations to the PSC.

Upon approval, the SharePoint Mg R&D Database will be publicly available in FY 2007.

In addition, recommendations on critical areas of R&D funding, that are not being addressed, will be made to the DOE Technology Area Development Manager.

Presentations

“Magnesium Automotive R&D in North America,”
J. Jackman, J. Carpenter, E. Nyberg, at the Intl. Conference on Mg Alloys and their Applications, Dresden, Germany, November 6, 2006.

M. Low-Cost Titanium Powder for Feedstock

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Contractor: Pacific Northwest National Laboratory

Contract No.: DE-AC06-76RLO1830

Objectives

- Investigate alternate powder and melt processing methods for low-cost titanium (Ti) materials.
- Evaluate processing methods to produce powder metallurgy (P/M) Ti products with International Titanium Powder, Inc. (ITP) powder.
- Evaluate the suitability of emerging Ti technologies for the production of low-cost Ti products for automotive applications.

Approach

- Perform characterization and analysis of the sintering behavior of the ITP powder. Provide feedback of results to ITP for use in process design.
- Develop low-cost feedstocks for P/M use in automotive applications from low-cost Ti tetrachloride (TiCl₄).
- Perform thin-section slab castings and roll to sheet to simulate and evaluate the use of continuous-casting methods to produce sheet materials.
- Survey the emerging technologies for the low-cost production of Ti powders and evaluate for use in automotive applications.

Accomplishments

- Observed decreased swelling in low-cost-TiCl₄-produced powders and attributed the improvement to the increase in the onset of sintering temperature that allows Na-bearing compounds to decompose.
- Developed press-and-sinter cycles that produced greater than 97% dense plates of cold-pressed (CP) Ti from the ITP powder.

- Developed sintering cycles that produced 95+% dense bars of CP Ti that exhibit ductility of up to 14% in selected samples from standard tensile tests using low-cost TiCl_4 .
- Produced and characterized CP Ti powder produced by ITP and DuPont from two impurity levels of TiCl_4 . The major powder characteristics showed no differences.
- Tensile-test samples produced from the low-cost TiCl_4 had very similar behavior to the higher-purity samples indicating that the low-cost TiCl_4 is a viable low-cost feedstock stream. The tensile characteristics of the sintered samples are strong functions of the oxygen equivalent for the powder and this was not affected by the TiCl_4 purity.
- Using a commercial P/M die, pressed approximately 100 gears to learn practical issues associated with the new Ti powders.

Future Direction

- Perform dilatometry, thermogravimetric analysis (TGA), microstructural analysis and x-ray diffraction (XRD) analysis to develop a sintering cycle that can eliminate Na impurities and improve sinterability.
- Investigate milling and compaction methods to reduce the high O and N content and/or fine powders.
- Continue the development of sintering cycles for the ITP powder with an emphasis on understanding the sintering mechanisms of the powder to increase ductility.
- Investigate in-die lubrication options for high-volume Ti die pressing.
- Evaluate alternate low-cost Ti feedstocks for powder or melt processing to wrought products.

Introduction

An automobile design trend that has received much attention has been the reduction of vehicle mass. Reducing mass can improve both performance and fuel economy. While design changes can play a large role in reducing mass, large reductions ultimately will require the substitution of higher specific strength/stiffness materials in place of carbon steel. Primary contenders in this race are high-strength steels, aluminum, and fiber-reinforced polymer composites. One material, not on this short list, but one that could provide further reductions, is Ti. Although Ti is light and strong, its role in the automobile has been almost nonexistent because of its exorbitant price. This high price is a direct result of the current Kroll production route which is time-consuming; energy-, capital- and labor-intensive; and batch-based.

However, new technologies are emerging that may change the characteristics of the Ti market. In particular, these technologies may reduce the Ti price sufficiently to allow it to compete in high-volume markets, possibly even automotive. This project examines the P/M behavior of Ti powder produced by a new process developed by ITP.

Approach

The production of low-cost Ti for automotive applications will require cost reductions in both raw materials and secondary processing operations. The approach to this project will be to evaluate the suitability of emerging Ti beneficial technologies for the production of low-cost automotive components. The ITP powder process produces an alloy powder with morphology very similar to other emerging technologies such as FFC Cambridge and MER anodic reduction. Because ITP can produce powders in sufficient quantity for evaluation, the ITP process will be used as the basis for the evaluation.

Results and Discussion

Previous reports^(1, 2, 3) of ITP powder processing indicated that Na compounds were assumed to be limiting the density and tensile ductility of the sintered pressing. TGA results of ITP powders indicated that Na compounds were present and began to decompose at temperatures near 500°C. Using previously-reported 1150°C sintering cycles⁽⁴⁾, plates were pressed, consolidated, and tested for mechanical properties using a standard ASTM E8 tensile sample tested at 12 mm/mm/minute strain rate. The tensile tests exhibited little or no ductility in the as-sintered condition. The failure strength of

the as-sintered sample was 510 MPa and occurred slightly after yield of the sample. The measured strain in the as-sintered sample was less than 0.07%. The samples that were as-sintered and rolled exhibited yield and ultimate strengths of 560 and 570 MPa, respectively, with an elongation of 4%. By decreasing the sintering time and increasing the temperature, better densification has been achieved allowing more rapid sintering to occur prior to the onset of swelling associated with Na-compound decomposition. Samples sintered at 1250°C for 20 minutes exhibit densities of 97+% of theoretical density and samples sintered for 8 hours had densities of 90%. With extreme sintering conditions, the swelling can reduce the density to below the starting density; an example is given in Figure 1a and compared to dense region of Figure 1b.

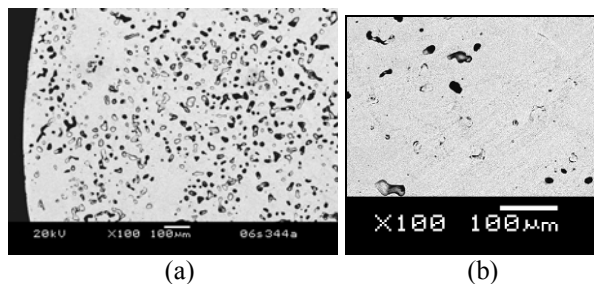


Figure 1. Sintered microstructures showing severe swelling with 8 hour 1250°C sintering (a) and a relatively dense region (b).

Ductility of up to 14% in machined tensile samples at strength levels of 450 to 500 Mpa has now been achieved. Table 1 has been included to show tensile strengths and ductilities observed with the new sintering conditions. The ITP powders made from low-cost TiCl_4 have exhibited slightly higher as-sintered densities, in all cases, when compared to the standard process. This is likely to be explained by the effect of trace impurities on the onset of sintering. The low-purity TiCl_4 ITP powder showed no swelling in dilatometer testing and the onset of sintering was increased from 400°C to 900°C, as shown in Figure 2. The significance of the temperature increase is related to the decomposition of Na-bearing compounds, where most known Na compounds decompose above 400°C and less than 900°C.

Table 1. Tensile properties for low and high purity TiCl_4 powders produce by ITP (R1 U2.2 and ITP-LP) and DuPont (D11001 and 500414).

Lot	TiCl_4 Purity	Theoretical Density, %	Strength		Elongation %
			Yield MPa	Ultimate MPa	
500414	High	92	413	553	14
D11001	Low	92	455	581	8
R1 U2.2	High	87	434	476	4
ITP - LP	Low	92	602	686	6

The standard allowable elements for high grade TiCl_4 are given in Table 2. The low-cost TiCl_4 exhibited elevated concentrations of trace elements compared to standard TiCl_4 and were less than 2000 ppm in the final metal powder. The ilmenite-based TiCl_4 , produced by DuPont, had less than 2 ppm Fe because of a distillation process used to produce FeCl_3 for sale to the chemical industry (resulting in reduced TiCl_4 cost).

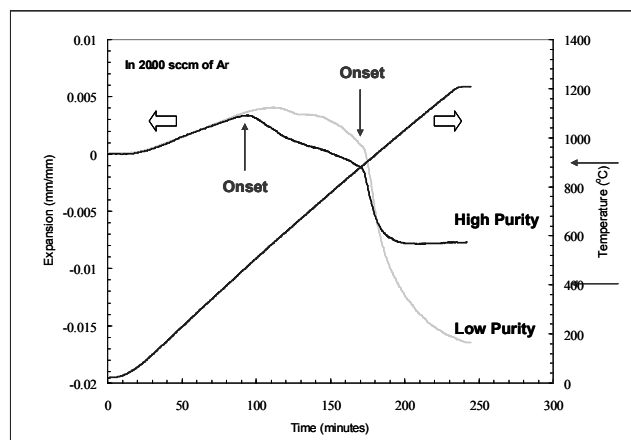


Figure 2. Dilatometer curves for the low-purity and high-purity TiCl_4 ITP powders. The presence of trace impurities have altered the onset of sintering and have increased the sinter-start temperature from 400°C to 900°C. The increase from 400°C to 900°C is significant to the decomposition of Na-bearing compounds.

The low-cost ilmenite-based TiCl_4 feedstock was received at ITP and DuPont and has been processed to powder using the each supplier's respective process. No processing problems were encountered with low-cost TiCl_4 and each supplier noticed little handling differences. Figure 3 is a micrograph of the ITP and DuPont powders showing typical morphology and structure found in Na-reduced TiCl_4 . Powders processed using standard and low-cost TiCl_4 powders exhibited no obvious difference

in powder morphology for both ITP and DuPont as shown in Figures 4 and 5, respectively.

Table 2. Comparison of chemical composition of standard and low-cost-ilmenite-based TiCl_4 .

Element	Standard TiCl_4 ppm
Sn	50.00
Si	10.00
Mg	10
Ca	10
V	3.00
Cu	1
Sb	5.00
Zn	5
Fe	1.00
Al	2
Pb	5
As	2.00
Cd	N/A
Mn	1
Ni	25
Nb	N/A
Zr	10
Ba	1.4
Cr	1
Co	1.4
Hg	<0.35

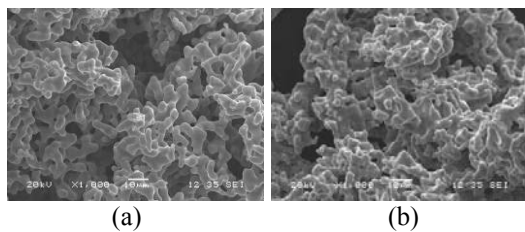


Figure 3. Powders produced by ITP (a) and DuPont (b) from low-cost ilmenite-based TiCl_4 showing morphology typical for Na-reduced powders and very similar structure for the two suppliers.

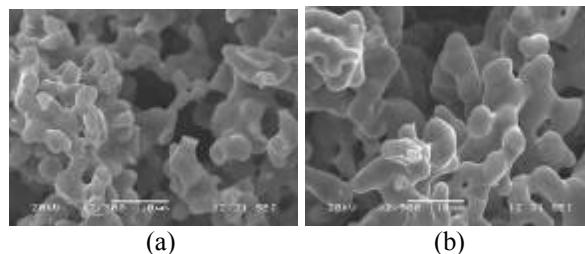


Figure 4. ITP powder produced with low-cost ilmenite-based TiCl_4 (a) and standard TiCl_4 (b) indicating little change in powder morphology. Note the ligament type structure in the as-received powders.

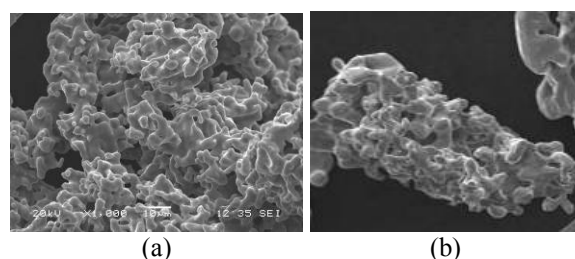


Figure 5. DuPont powder produced with high-purity TiCl_4 (a) and low-cost TiCl_4 (b) indicating little change in powder morphology.

The particle-size analysis of the as-received powders indicated that DuPont and ITP processes produce a different distribution; however, the low-cost TiCl_4 did not affect particle distribution. Figure 6 is a histogram showing powder-size distribution for the ITP and DuPont powders made from low- and high-purity TiCl_4 .

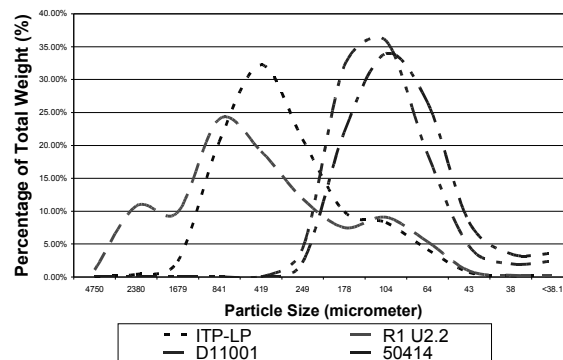


Figure 6. Particle-size distribution for low-cost TiCl_4 DuPont and ITP (50414 and ITP LP, respectively) and standard (D11001 and R1 U2.2, respectively) TiCl_4 powders. The distribution indicates a difference for each supplier but no difference for TiCl_4 purity.

The ITP powder and DuPont powders had different trace element levels, which were attributed to slight differences in the TiCl_4 used at both suppliers. Summary of the typical impurities found in the powders are in Table 3. O content for the powders was found to range between 1780 and 2400 ppm and was lowest (1780) in the low-purity ITP powder and highest (2400) in the high-purity ITP powder. The DuPont low- and high-purity TiCl_4 powders were 2100 and 1890 ppm O, respectively. Although the differences in O appear slight, the content variation is enough to alter the mechanical properties substantially. The primary differences in the powders were the N, Na and Cl contents. The low- and high-purity ITP powders had 50 and 80 ppm, respectively, and the DuPont powder was below the detectability limit of 20 ppm (lower limit N test are being performed). N is an interstitial element and behaves similar to O in Ti. The Na content for the ITP and DuPont powders were 330 and 110 and 1300 and 1200 ppm for the low- and high-purity TiCl_4 , respectively. Cl was 1100 and 1400 and 19 and 21 for the low- and high-purity TiCl_4 DuPont and ITP powders, respectively. The form of Na and Cl in the ITP powder is unclear and could not be found in SEM analysis of metallographically-prepared samples or fractured surfaces using EDS and WDS analyses, indicating that it may be in the powder solid solution; however, NaCl particles were found on the fracture surfaces of the DuPont tensile samples and would be expected to reduce mechanical properties. Figure 7 shows an example of a Na- and Cl-rich particle found on the fracture surface of a DuPont-powder tensile sample.

Table 3. Comparison of metal powder chemistry for ITP (HP and LP) and DuPont (D11001 and 500414) low-cost TiCl_4 (ITP-LP and D11001) and standard TiCl_4 (ITP-HP and 500414).

	ITP-HP	ITP-LP	D11001	500414
Element	ppm	ppm	ppm	ppm
C	93	55	74	105
Cl	19	21	1100	1400
N	77	47	<20	<20
Na	330	110	0.13%	0.12%
O	2400	1780	2100	1890
O-equiv	2554	1874	2100	1890
BET (m^2/g)	0.31	0.31	0.30	0.45

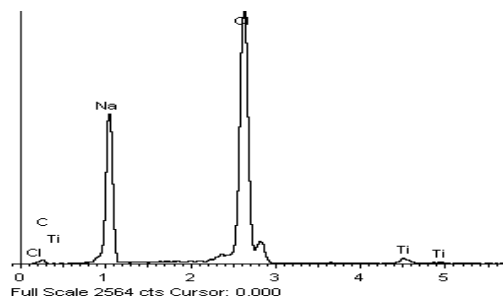
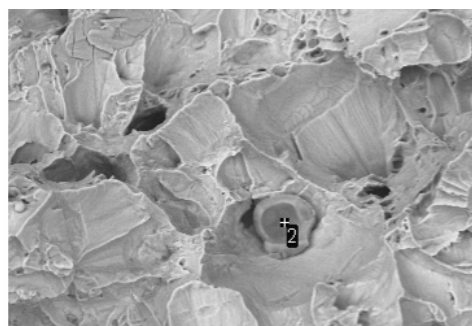


Figure 7. Na- and Cl-rich particle, noted as 2, in SEM fracture surface (below) and corresponding EDS analysis (above).



The trace elements found in the TiCl_4 and in the powder were not found at fracture surfaces or in particulates within the structure, indicating that, as predicted from the binary phase diagrams, all of the impurities are in solid solution. This favorable result indicates that no gross intermetallics were formed and that the trace elements are not expected to impact properties such as fatigue or ductility. A solid-solution strengthening effect may be found, however, given the elevated O and N contents of the powders; the low levels of trace elements may be difficult to discern. Fracture-surface analysis shown in Figure 8a and b for ITP and DuPont powders, respectively, showed no preferred initiation site and exhibited a mix of ductile rupture, cleavage and porosity.

The high strength and corresponding low ductility of the tensile samples continues to be problematic. A simplified oxygen-equivalent equation ($\text{O}+2\text{N}$) was applied to the four powder types. The oxygen equivalent shows that all strength variation within the samples can be attributed to the O and N content, as shown by the linear correlation in Figure 9, with oxygen equivalent and 0.2% offset yield. This is a favorable result with respect to the low-cost TiCl_4 in

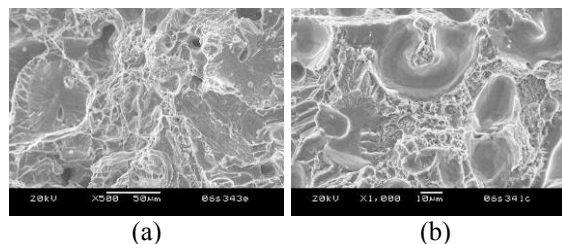


Figure 8. Fracture surface of sintered compacts of ITP (a) and DuPont (b) indicating a mixed failure mode of ductile rupture and cleavage. No trace elements were found on the fracture surfaces indicating that the low-cost TiCl_4 had not adversely affected ductility.

that trace elements are having a minimal effect on the properties; however, the O and N content must be better controlled.

In pressed and sintered samples, the O content is elevated by approximately 1200 ppm. The source of the increase is each prior process step (milling (700ppm), pressing (200ppm) and sintering (300ppm)) and must be controlled in a different manner than currently used. The initial step will be to screen out fines (less than 400 mesh) that have O contents in excess of 4000 ppm. To date, milling has been done using a Spex mill and has produced nearly 25 weight percent fines containing 4000 ppm O (milling is done in an Ar-filled glove box, however, the powders must be passivated in air for safe handling). Therefore, a milling process will be employed to reduce the generation of fines.

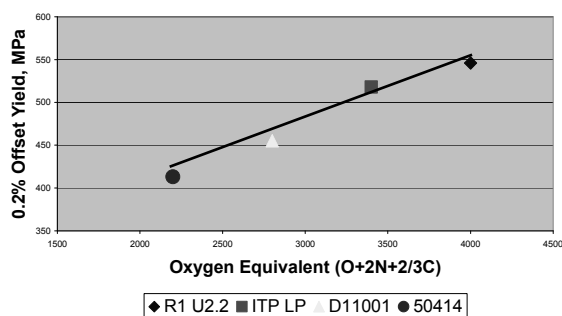


Figure 9. Correlation of yield strength and oxygen equivalent for low-cost TiCl_4 DuPont and ITP, 50414 and ITP LP, respectively, and standard TiCl_4 powders D11001 and R1 U2.2 for DuPont and ITP, respectively.

Powders milled at PNNL were pressed using a high-rate commercial P/M die located at Western Sintering, LLC, Richland, WA. The die used was a gear developed for commercial production of a helicopter rotor-balancing assembly that has been discontinued. A green pressing of the gear from low-cost- TiCl_4 ITP powder can be found in Figure 10. The trials provided insight into the characteristics needed for the use of Ti powder in commercial Ti applications. The trials were performed using a hydraulic press operated at an equivalent rate of 45 parts per minute at pressing pressures of 80,000 pounds per square inch (40 tons per square inch). The initial trials were performed without lubrication due to Ti's reactive nature and the potential for the very high green strength part being more robust; however, within 10 pressings, cracking was observed in the pressed part. The cracking was attributed to galling in the die resulting in tensile stresses during part ejection. The die was cleaned and a series of pressings were made using lithium stearate die lube with very little improvement. Additionally, the fines were left in the powder blend and caused interference with the punch and die. Therefore, a second series of trials were performed using powders blended with various lubricants used in commercial powder-metal production which resulted in no improvement. For the trials it was learned that 1) the ITP powder must be milled to produce a low fraction of fines and a separation step must be added and 2) in-die lubrication will be required to minimize reaction with the Ti and provide an adequate barrier to prevent galling.

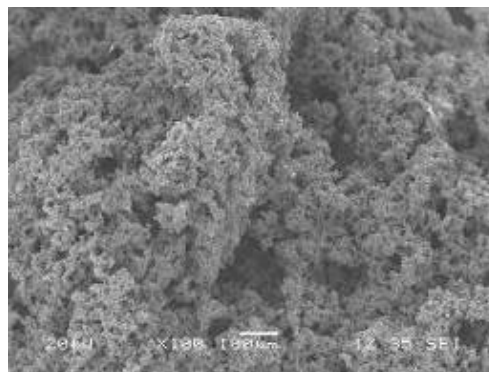


Figure 10. Typical as-received ITP powder that exhibits a tapped density of approximately 8% of theoretical.

Lubrication is commonly used in P/M; however, lubrication is more complicated in Ti due to the reactivity. In Fe-based P/M, lubricants are added directly to the powder and are either removed during a pre-heat portion of the sintering cycle or used to react with the powder and form wear-resistant carbides. In extreme cases of die complexity, in-die lubricants are used with Fe-based P/M to facilitate part compaction or ejection. However, Ti will react readily with common powder and die lubricants and die materials such as Fe-based steels and the binder of carbide(W, Hf etc...)-cemented carbide tools. In order to evaluate the suitability and effectiveness of powder and die lubes, an instrumented die has been constructed that will enable direct measurement of friction factor and compaction and ejection force. See Figure 12.

The powders produced by ITP exhibited an open pore structure, shown in Figure 11, and, as a result, have a relatively low tapped density of approximately 8%. Although a tapped density of 8% is workable for many P/M applications, ideally, the tapped density will be higher. As a result, milling trials were initiated at PNNL to break down the powder and develop a higher tapped density. The trial indicated that ITP powder, although very ductile, was readily milled and that tapped densities could be increased to in excess of 45%. As mentioned previously, the fraction of powder less than 400 mesh is 25 weight-percent and contains more 4000-ppm O and 290-ppm N using the current milling practice. This practice will be re-evaluated, and a balance between O content and apparent and tapped densities will be established. Initial milling trials using less-aggressive media have improved tapped density and powder morphology, as shown in Figure 13, where the open pore structure shown by figure 10 has been compacted into a more globular network, without fracture, into smaller particles. In limited trials, the milling process development is ongoing and has shown improvement in both green and as-sintered densities.

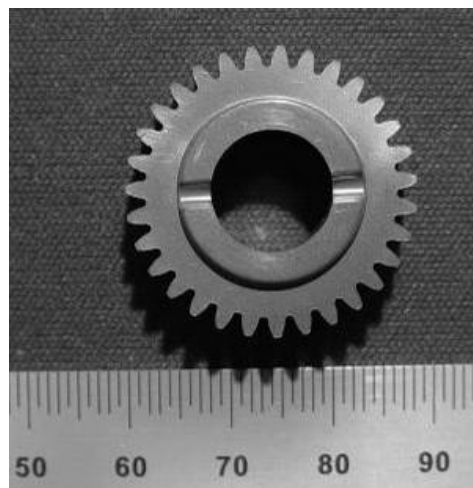


Figure 11. Commercial die-pressing using low-cost TiCl_4 ITP powder.

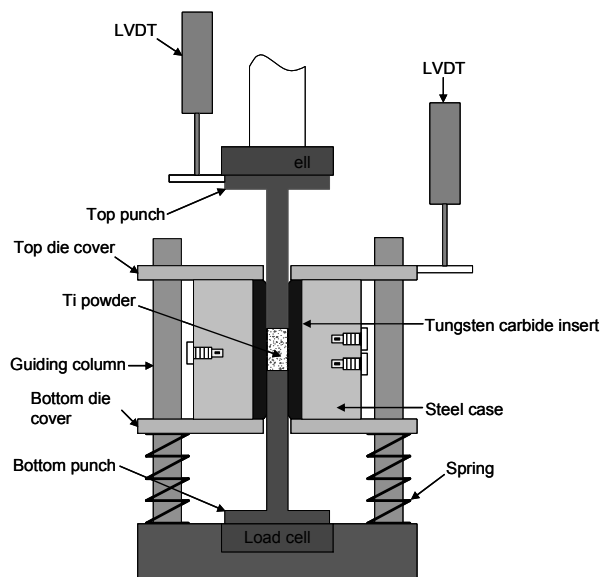


Figure 12. Instrumented die to be used for lubrication development.

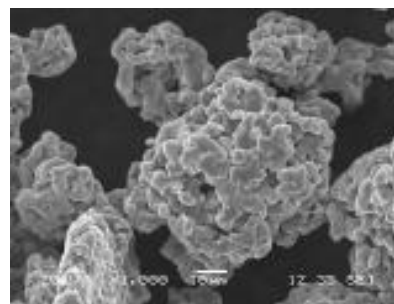


Figure 13. Alteration of ligament structure (compared to Figure 10) for ITP milled using less-aggressive parameters.

Conclusions

As indicated by the strength and ductility levels produced in the vacuum hot-pressed samples, the powder produced by ITP can develop near wrought-like properties in CP Ti.

Sintering conditions for the ITP processed powders have been developed to produce ductility of 10% in selected samples, with average values at approximately 8%.

The added trace elements have not affected the tensile properties of samples machined from sintered bars. The largest effects on mechanical properties are from O and N.

Optimization of the sintering cycle must be performed to maximize ductility, and will be focused on the elimination of Na-induced swelling.

The morphology, surface area, and particle-size distribution of the low-cost ilmenite-based TiCl_4 was very similar to the standard TiCl_4 powders.

Powder milling, compaction, and sintering methods will be evaluated for O and N reduction. Commercial die pressing will require that the powders are milled to reduce the fraction of fines.

Commercial die pressing will require the use of an in-die lube system to form a barrier between the die steel and Ti powder.

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N. Low-Cost Powder Metallurgy Technology for Particle-Reinforced Titanium Automotive Components: Manufacturing Process Feasibility Study (AMD 310ⁱ)

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Contractor: U.S. Automotive Materials Partnership

Contract No.: FC26-02OR22910

Objective

- Demonstrate production-intent process scheme for fully-densified titanium-alloy, powder-metallurgy (PM) composite samples.
- Benchmark process capability using commercial-grade titanium powder feedstock and follow with one of the proposed low-cost titanium powder materials. Blend additives to achieve final titanium-alloy material with reinforcement.
- Perform microstructure characterization and interfacial studies.
- Confirm test specimens are crack-free by nondestructive evaluation method (Lawrence Livermore National Laboratory).
- Generate static mechanical properties and perform failure analysis.
- Perform a technical cost modeling study on the novel ADMA Products, Inc., process and establish sensitivity of each processing step for cost-effectiveness.

Approach

- Use titanium metal feedstock to produce blanks in simple shapes via the ADMA manufacturing process that will then be machined into coupons for mechanical property determination.
- Conduct microstructural and interfacial studies together with mechanical property testing.
- Perform a technical cost model on the ADMA manufacturing process.

Accomplishments

- Produced powder blends of Ti-6Al-4V material from Sodium Reduced Ti sponge fines with and without reinforcement (benchmark material).
- Received powder blend of Ti-6Al-4V material from International Titanium Powder (ITP) without reinforcement (low-cost alternative).
- Die-pressed powders in 0.500-in.-diameter carbide tooling to 0.500-in. thickness for metallographic examination.
- Compacted and processed powder blends into 3 inch x 5 inch blanks for tensile samples.
- Sintered in vacuum furnace, optimized heat treatment.
- Machined blanks into tensile samples.
- Completed metallographic examinations and tensile tests.
- Completed fracture analysis on composite material.
- Completed cost model on ADMA manufacturing process.
- Assessed cost model and mechanical properties against decision-gate criteria.
- Completed USAMP final report.

Introduction

The goal of this concept-feasibility study is to develop a low-cost PM manufacturing process to obtain fully-dense parts based on current commercial-grade materials and a novel processing technology. The study will use particle-reinforced titanium metal feedstock in conjunction with PM press-and-sinter technology to manufacture simple parts for testing. A technical cost model will be performed to document the cost of the manufacturing process. The decision gate criteria are (1) a cost-competitive manufacturing process and (2) acceptable microstructure and mechanical properties that have been identified for connecting rods targeted for high-performance reciprocating engine applications.

Low reciprocating-mass components are being sought by the domestic automakers in the FreedomCAR partnership for the next-generation of high-efficiency engines. The USAMP research objective for Ti has been set at 50% weight

reduction and at < 3 times of the cost of powder forged iron-base connecting rods in production. Other benefits of titanium connecting rods due to high strength/weight ratio are, enhancing the horsepower without changing the engine architecture, reducing NVH to potentially eliminate the balance shaft system, etc.

ADMA Products, Inc. has developed a full-density (99% dense) powder metallurgy press-and-sinter process for titanium and its alloys. The process with near-net shape capability offers considerable cost savings over current isostatic pressing and/or hot forging/extrusion type processes. The study plans to extend the technology to titanium metal matrix composite for connecting rod application.

The approach is to use Ti metal feedstock to produce blanks in simple shapes via the ADMA process that will then be machined into coupons for mechanical property determination. Microstructure and interfacial studies together with mechanical property

testing will be carried out by the team including outside sources jointly selected.

Target mechanical properties to be reached are ultimate tensile strength and yield strength of 750 MPa (107 KSI) and 670 MPa (96 KSI), respectively with elongation exceeding 6%. Furthermore, microstructure has to be uniform and free of segregation. Had the study demonstrated the ability to reach the set property target, the costs of materials / manufacturing processes developed have to be established to ensure that it is cost competitive. Development of actual component would be the next step for consideration.

Conclusions

The study demonstrated the ability to reach the decision gate target. Room-temperature tensile properties for as-sintered Ti-6Al-4V alloys have met the target values set for the study. It would produce Ti alloys reaching the fully-densified state in simple geometry. The whole operation, using blended elemental powders and simple press-and-sinter P/M operation, was carried out in a cost-effective manner.

The process also appeared to be capable of producing nearly full-density Ti metal-matrix composites (MMCs) in a cost effective manner. The Ti-6Al-4V metal matrix was successfully reinforced with carbide particles, via the press-and-sinter P/M technology in conjunction with the blended elemental powder approach. Reinforcement improved modulus of elasticity up to 20%.

The project covered 17 Ti-base alloy compositions. Some of them were processed with the conventional press-and-sinter P/M technology, and others were hot pressed, forged and with limited heat treat to optimize microstructure and properties.

The original intent was to evaluate the concept of producing fully densified parts via powder metallurgy approach starting with a hydrogenated titanium powder. However, neither the hydrogenated powder nor hydrogenation process was available at the beginning.

Only high-purity titanium powders were used for this study - reduced by sodium, magnesium, calcium, to name a few. The goal of full density

consolidation remained the same. Titanium powder from ITP Armstrong process became available toward the end of this study.

Future

This project has ended and report filed with the USCAR.

Recommend future work includes:

1. Additional refinement on sintering cycle for Ti-MMC to improve properties in the already full density condition. As stated, fully densified state is the first (major) step and a pre-requisite for any further property improvement from the consolidation point of view (via P/M approach). Certain properties like fatigue, fracture toughness, corrosion resistance, etc can be improved further while remaining in the full density state.
2. Cost analysis based on the developed materials and processes should then be performed to ensure its cost effectiveness.
3. Hydrogenated powder approach should be explored in search for more cost effective manufacturing process.

ⁱ Denotes project 310 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.

O. Powder-Metal Performance Modeling of Automotive Components (AMD 410ⁱ)

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Objective

- Develop and evaluate math-based models for powder-metallurgy component design and performance prediction. An existing USAMP microstructure-property model for castings will be extended to powder metallurgy (P/M) for practical application in low strain-rate (design and durability) and high strain-rate (toughness-driven impact

strength) environments. This model will be utilized to evaluate and optimize two component designs (a main bearing cap and a gear) as affected by material (ferrous and non-ferrous) and manufacturing processes (compaction and sintering), and will accommodate a company's analytical codes (initially ABAQUS, then other codes such as LS-Dyna, Ansys, etc.). The flexibility of this model will facilitate the evaluation of lightweight materials (such as aluminum and titanium) for future component applications.

Approach

- Determine current powder-metallurgy standards publications, component design guidelines, manufacturing, and evaluation methodologies. Provide a selection of metal powders that can satisfy design performance requirements, component design guidelines, and manufacturing and testing specifications across industry participants (Task 1).
- Evaluate and develop numerical modeling techniques to predict mechanical properties throughout P/M component sections. The transition of current materials and designs to process structural automotive P/M components creates the need to predict the properties of the component in all sections of the design. In addition, there is the necessity to provide the least-cost, lowest-mass product designs and reduced development lead-time. Adapt and/or re-develop existing math-based models which are capable of accurately predicting P/M component structures and properties throughout the compaction and sintering processes (section size, density variation, dimensional tolerances, potential for cracking), alloys and process parameters (machine functions, tool and powder temperatures, strain-rate, friction and pressure). Capture the history of a P/M part through its pressing, sintering, and life-cycle performance history using the developed multiscale methodology. (Task 2).
- Develop component- and vehicle-level testing to validate durability, quality control and performance of P/M automotive parts. Quality control for P/M parts production involves several process factors such as powder properties, press settings, tooling design, and furnace condition. Determine these process factors in terms of their impact on process variations and quality improvement. Use optimization and statistical techniques to help determine the main factors affecting the final component. Perform validation experiments in which actual boundary conditions from real processes will be used to fracture the components. This will ensure understanding of the quality effects on the product along with the modeling effort. (Task 3).
- Manage and report program activities. The proper execution of this task will greatly enhance the value of the overall program. The types of reports and guidelines generated from this program, i.e., will be in accordance with DOE and USCAR requirements. (Task 4).
- Perform technology/commercial transfer throughout the automotive value chain: Unlike aluminum, plastics and steel, there are no major R&D/technical institutions fostering the necessary infrastructure to support the large-scale application of automotive P/M components. For this reason, if the auto industry wishes to take advantage of P/M's potential weight and cost-reduction opportunities, nurturing through programs sponsored and directed by USCAR will be required. The project team will request the professional support of societies to publish notices of meetings and project information, as released by the project team. (Task 5).

Accomplishments

- Compaction of TR bars and cylindrical samples at different densities for three different powders.
- Compaction Modeling Status: Simulation of cylindrical samples and comparison with compaction data.
- Ongoing material characterization of the FC-0205 Ancorsteel powder provided by Hoeganaes.
- Compaction validation experiments at Cincinnati, Inc. to support the modeling effort.
- Sintering Modeling Status: Development of algorithm for implementation into ABAQUS/Standard.
- Establishment of a partnership with Metaldyne, LLC for the optimization of P/M automotive parts.

Future Direction

- Continue the microstructural evaluations and mechanical property tests on P/M cylinder geometry to determine microstructure-property relations during compaction, sintering, and in-service duty life. With the above software developed, the model will be correlated to these microstructure-property relations.
- Develop die compaction of cylindrical specimens using cylindrical dies with holes of different diameters to replace the triaxial compaction tests, and determine the cap surface plots.
- Determine the interparticle friction coefficient, using a simple Coulomb law of friction, by measuring the tangential forces at the contact surface, and determine the influencing parameters contributing to the friction effects.
- Develop the expression of the tangent matrix $\Delta\sigma/\Delta\epsilon$ to implement the developed compaction model into the finite element code ABAQUS/Standard to predict the springback of compacted parts during ejection.
- Implement the sintering model in ABAQUS/Standard.
- Predict the material state during the powder compaction and sintering processes with the developed math-based models for a main bearing cap provided by Metaldyne, LLC.
- Measure the density of each piece of parts compacted at Cincinnati, Inc. by means of Archimedes' principle and hardness testing, and compare the results with modeling.
- Perform tension, compression, torsion and fatigue tests on material samples provided by Metaldyne
- Validate the process model (including tool geometry, friction, tool and metal temperatures, and pressure) and property models on the P/M bearing cap and gear with experiments, in collaboration with the partner Metaldyne.
- Work in collaboration with Chaman Hall (Metal Powder Products – MPP) on lightweight materials such as aluminum for the bearing cap.
- Explore the possibility of using an adaptive meshing procedure with CUBIT software developed at Sandia National Laboratories to model the powder flow during compaction and avoid mesh distortion.
- Explore the DEM software provided by the USACE Engineer Research and Development Center (ERDC) to study die filling and powder transfer, to determine the density distribution before compaction.

Introduction

The Powder Metallurgy Performance project started in October 2004 at the Center for Advanced Vehicular Systems (CAVS) with guidance from the Big Three automakers (General Motors, Ford, and DaimlerChrysler) and the Center for Powder Metallurgy Technology of North America (CPMT). After the literature review and the establishment of a test matrix during the first year, the major accomplishments during this second year were (i) the run of closed-die compaction at different densities of TR bars and cylindrical samples necessary for the material characterization, and simple-shape parts on a Cincinnati, Inc. press for the validation of our model; and (ii) the validation of the P/M compaction constitutive model that was implemented in ABAQUS/Explicit. In the second year, the ongoing activities are (1) the development of a stress integration algorithm to implement the

sintering model in ABAQUS/Standard, (2) the characterization of the FC-0205 powder, and (3) quantification of powder compaction data on simple-shape green parts pressed at Cincinnati, Inc.

Powder Characterization

Several experiments were conducted on the FC-0205 steel-based powder provided by Hoeganaes for the microstructural characterization and mechanical property determination. Three variants of the FC-0205 were considered in this work; the two first powders contain different percentages of Acrawax (0.6% and 1.0%), and the third powder was used at Cincinnati to run compaction tests (with 0.6% lubricant). These three powders were denominated powder I, II and III respectively. A large quantity of green samples were compacted at Penn State University and then analyzed at CAVS using different equipment such as SEM, optical

microscope, X-ray computed tomography (CT), etc. These experiments are part of the ongoing modeling effort to determine the model parameters and quantify the microstructure.

Table 1. Average density and dimension of green round and TRB specimens.

Round Specimen – 1.25 inch diameter (5 samples per density – Total: 90 samples)					
Average Density (g/cc)			Average Height (inch)		
I	II	III	I	II	III
6.58	6.61	6.63	0.7623	0.7461	0.7432
6.61	6.69	6.77	0.3753	0.3709	0.3629
6.59	6.69	6.77	0.2003	0.1989	0.1986
7.18	7.06	7.19	0.7891	0.7986	0.7824
7.17	7.06	7.17	0.4513	0.4506	0.4438
7.09	7.05	7.15	0.2364	0.2363	0.2360
TRB specimen – 0.50 inch thick (5 samples per density – Total: 120 samples)					
Average Density (g/cc)			Average Thickness (inch)		
I	II	III	I	II	III
5.93	5.98	5.92	0.4889	0.4833	0.4868
5.75	5.81	5.72	0.4779	0.4722	0.4789
6.08	6.12	6.10	0.4994	0.4916	0.4926
6.30	6.32	6.30	0.4998	0.4962	0.4962
6.54	6.52	6.52	0.4953	0.5001	0.4972
6.82	6.81	6.81	0.5015	0.4998	0.4990
7.01	7.02	7.10	0.5026	0.4973	0.4913
7.33	7.10	7.22	0.4932	0.5066	0.5004
TRB specimen – 0.25 inch thick (20 samples per density – Total: 540 samples)					
Average Density (g/cc)			Average Thickness (inch)		
I	II	III	I	II	III
5.63	5.65	5.61	0.2509	0.2470	0.2496
5.83	5.81	5.80	0.2501	0.2481	0.2487
6.09	6.06	6.04	0.2464	0.2446	0.2468
6.29	6.31	6.32	0.2488	0.2445	0.2457
6.42	6.46	6.45	0.2495	0.2450	0.2475
6.63	6.66	6.58	0.2490	0.2461	0.2486
6.81	6.84	6.87	0.2487	0.2471	0.2467
7.06	6.97	7.02	0.2495	0.2487	0.2480
7.19	7.08	7.30	0.2498	0.2507	0.2415

Compaction of green compact samples

Using a 60-ton Gasbarre press at Penn State University, round and transverse rupture bar (TRB) specimens were compacted at different densities (Table 1). The press is equipped with several sensors to record the force of the lower and upper

punches, and also the displacement of the upper punch and the die plate for each sample. Because the powder was fed manually using a simple shoe, a slight variation in density from one sample to another was observed. To obtain the desired density and thickness for each series, a trial-and-error method was applied by adjusting manually the tonnage and the fill depth.

Densities and dimensional measurements for 1.25-inch-diameter round specimens were made at Penn State using a caliper (0.0005”) and a lab scale (1mg). The same measurements for TRB samples were performed at CAVS using a caliper (0.0005”) to measure the length of 1.25 inch, a micrometer (0.00005”) to measure the width of 0.50 inch, and the thicknesses of either 0.50 or 0.25 inch, and a lab scale (0.1mg). All data are saved in Excel files. Press loads and displacement were plotted only for the first sample of each group.

TRB specimens will be used for powder characterization, such as green strength, sintering applications, hardness testing and X-ray CT. Round specimens will be used for a first validation and calibration of the compaction constitutive model developed at CAVS by looking at the final average density and force-displacement curves.

Cold isostatic compaction (CIP) was also conducted at Penn State University for 5 different pressures (10, 20, 30, 40 and 50 tsi). The volume of the samples still needs to be cautiously measured since certain samples were broken into several pieces.

Green Strength

Green strength was measured for TRB green samples of 0.25 in. and 0.50 in. thickness according to the MPIF Standard Method 15 for the three variants of the FC-0205 powder. The tests were performed on the three first TRB samples of each density in Table 1.

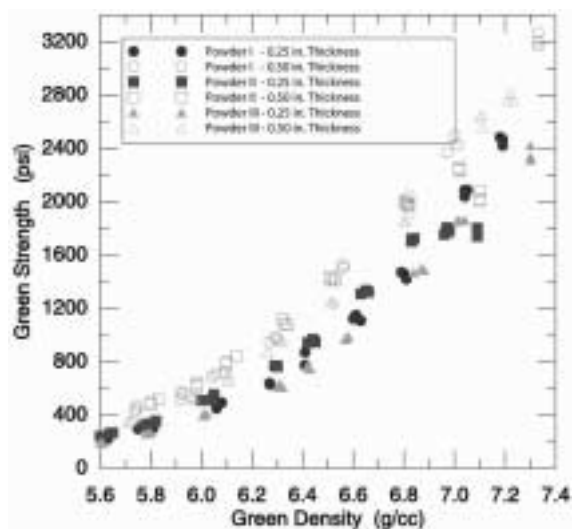


Figure 1. The effect of compaction pressure on the green strength of FC-0205 powders.

Particle shape and size distribution

A representative sample of powder was collected for the particle-size characterization analysis. In order to avoid particle agglomeration, an ultrasonic agitation was sufficiently applied to disperse the cluster of particles and assure a proper particle-size characterization. This process was repeated for every tested powder.

The particle-size analysis was achieved using a sieve analysis by following the MPIF standard method 05. Three different screens were weighed and stacked with decreasing mesh opening. A 100g powder sample was loaded on the top of the screen and agitated in a sieve-shaking device for a period of fifteen minutes. After the agitation, each screen was weighed calculating the percentage of powder sample retained or passed throughout the mesh. The particle-shape distribution was determined from a microscopic imaging method.

Tap Density

The tap density was determined using the Hall flowmeter according to the MPIF Standard Method 04, obtaining 3.13 g/cm^3 . The apparent density was determined using the Hall flowmeter, obtaining 3.09 g/cm^3 .

Chemical Composition

The chemical composition was determined using two different methods, an optical-emission spectrometer (OES) and an EDX mapping using a SEM.

The optical-emission spectrometer creates an arc or spark discharge vaporizing the sample, and the atoms and ions contained in the atomic vapor are excited into emission of radiation. The radiation emitted is passed to the spectrometer optics via an optical fiber, where it is dispersed into its spectral components. From the range of wavelengths emitted by each element, the most suitable line for the application is measured by means of a photomultiplier. The radiation intensity, which is proportional to the concentration of the element in the sample, is recalculated internally from a stored set of calibration curves and can be shown directly as percent concentration. This procedure was repeated 21 times using different density samples to obtain an average and accurate value.

Energy-dispersive X-ray (EDX) in the Scanning Electron Microscope (SEM) was used to identify the elemental composition of the specimen. A loose powder sample was set on conductive tape and observed under the SEM. A representative image that contained most of the powder mixture was selected as our region of interest. From this method the location of the major alloying components like carbon and copper in the region of interest selected before, were obtained using the EDX spectrum that shows the energy level received for each element. The element weight percentage of a selected powder sample was also determined.

Figure 2 shows the dispersion of the elements in the FC-0205 iron powder (only a sample from the first powder was analyzed).

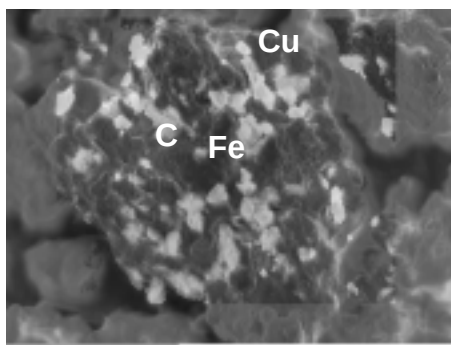


Figure 2. Mix of all major compounds in the iron powder FC-0205.

Microstructural Features

The TRB samples were cold mounted in order to separate the “pull-out” artificial pores from the true pores. The specimens were ground and polished according to standard practices. The etchant used for the examination of the microstructure was 2 % nital. The sample preparation was performed following standard procedures to preserve the pores and grain structures.

The grain-size distribution (Table 2) was obtained using an intercept procedure. The grain size is determined by the number of times a test line cuts across, or is tangent to, grain boundaries.

Table 2. Grain Size number for the green compacted samples at 6.8 g/cc.

Compacted Density g/cc	Grain Size No. G	Grains/ unit area	Average Grain Area	Average Diameter
		No./in at 100x	μm^2	μm^2
6.8	7.50	90.51	7.13	26.7

All six sides of the TRB sample were analyzed to obtain an average grain-size number (G) for each density.

An image analyzer software developed at CAVS was used to measure the porosity, pore nearest neighbor and the pore volume fraction. Microstructure images were taken in an optical microscope at a 100 μm resolution for each density and each side of the TRB samples. The software calculates and highlights the pore area, the minimum, mean and maximum first nearest

neighbor. Further calculations are necessary to calculate the porosity and the pore volume fraction.

The images for the 7.0 g/cc and 7.2 g/cc green samples that have been taken are getting processed to obtain the values of Table 2.

X-ray CT

For crack detection and density measurement, CAVS facilities recently acquired a Phoenix V/Tome/X Computed Tomography system with the 225D directional target tube and the 160NF transmission target tube.

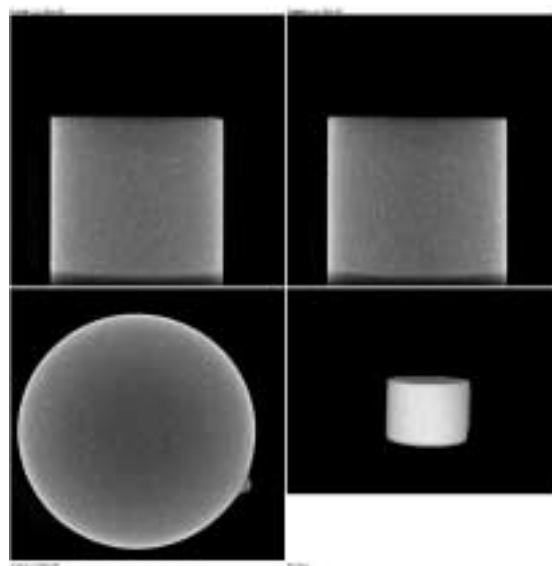


Figure 3. CT scans of 9-mm-diameter compacted samples after being machined.

Figure 3 shows the reconstruction of the density distribution of 9-mm-diameter round samples of different known densities. The samples were scanned using the same scanning conditions (beam current and voltage). Two copper filters of one millimeter thickness were used to avoid beam hardening artifacts. The attenuation of the X-rays was measured by an array of detectors over many views (X-ray paths) by stacking contiguous two-dimensional images and mathematically reconstructing them into 2D or 3D.

Quantitative interpretation of reconstructed CT images in terms of the mass density or the composition of the object usually is done by

assuming an attenuation that is linearly dependent on the mass density or material thickness, especially in dense materials. However, this is only true for monochromatic sources [Van de Casteele et al., 2002]. As with most of the CT systems, the V/Tome/X CT system uses polychromatic X-ray sources, which can produce significant artifacts in the reconstructed image due to non-linearities. This makes the translation of the CT values inexact or not possible at this time. CAVS is looking currently for a solution to overcome the complexity of the projection data and eliminate statistical noise artifacts. Different methods currently exist to minimize these artifacts. A method for compensating non-linearities divides the detected spectrum into a low- and high-energy region, and the resultant signals are processed to obtain a photoelectric component and a Compton scattering component [Macovski et al., 1976]. Another commonly-applied correction method is based on a linearization procedure where the measured nonlinear relationship is fitted with polynomials [Van de Casteele et al. 2002].

Validation of Simple Compaction Parts

As part of the CAVS modeling effort, CPMT and CAVS conducted a validation trial of a multi-level P/M part (Figure 4) at Cincinnati, Inc. with the help of Kenneth Cradler and two other assistants, all three are employees of Cincinnati, Inc. The goal of this trial was to validate the powder-compaction model in terms of the density distribution, the powder transfer during compaction, and the fracture mechanism during the ejection process.

The FC-0205 powder III was used and the apparent density value was measured at 3.29 g/cc during these runs. The parts fell into 3 groups based on overall average density (6.45, 6.80 or 7.10 g/cc). The trials were conducted by varying the fill depth of each column, initially with an even ratio of compaction in each column, and then by adding or reducing the amount of fill (powder) above the lower punch by re-positioning it. This changes the amount of powder to be compacted and, therefore, affects compaction response. The pressure remained the same but the density achieved changed (Table 3). The columns 1, 2, 3 and 4 correspond respectively to the heights 0.870 in., 0.475 in., 1.000 in., and 0.510 in Figure 4.

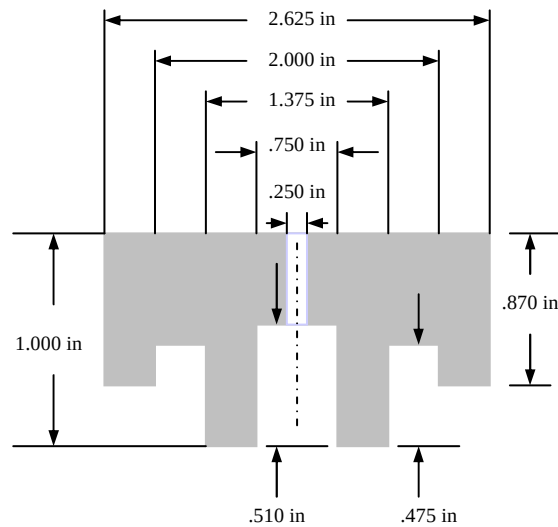


Figure 4. Drawing of the Cincinnati Inc. sample part.

The pressing condition of the upper punch (overall press tonnage) and all press platen motions, in terms of displacement versus time, were obtained and recorded through the data acquisition system (DAS) and are available through the Windaq software. Measurements were taken using displacement sensors attached to each platen with individual data points acquired about every 100 milliseconds. These data will be used in a finite-element input file as boundary conditions.

After ejection, cracks were observed in the series where the powder fills were modified by a decrease in column 1 and an increase in column 3 (series 3 and 5 in Table 3). Parts were ejected with no apparent crack in the series where each column depth was filled with an even ratio of compaction (Series 1, 4 and 7). No apparent crack was observed in series 6 also, where the test transferred powder from column 1 and added it to column 2.

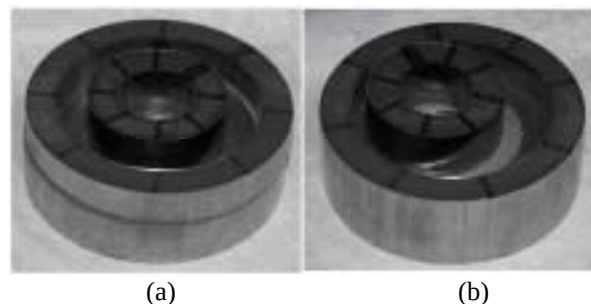


Figure 5. (a) Crack in the skirt region after ejection. (b) Crack in the center hub after ejection.

In series 3, the amount of powder transferred from column 3 to column 1 did not actually occur if the density was to be equalized during compaction. As a consequence, a crack was seen in the skirt (lower portion) region of column 1 at the step between column 1 and column 2 powder heights (Figure 5). We believed the low green strength at this density may have also been a contributing factor. In series 5,

the test changed the powder fills by reducing the fill in column 1 and increasing the fill in column 3 to compensate so the overall part density remained at 6.80 g/cc. Due to the extensive transfer of powder, the parts cracked in the skirt region (Figure 5a) or in the center hub (Figure 5b), depending on the press motions and compensating air pressure. Ten pieces were run in each mode.

Table 3. Cincinnati, Inc., Test Runs.

Series #	Samples	Average Density g/cc	Fill Position Column 1, in.	Fill Position Column 2, in.	Fill Position Column 3, in.	Fill Position Column 4, in.
1	10	6.45	1.644	1.017	1.943	0.809
2	10	6.45	1.675	1.020	1.821	0.809
3	10	6.45	1.594	1.027	2.157	0.809
4	11	6.80	1.762	1.064	2.027	0.809
5	20	6.80	1.649	1.064	2.229	0.809
6	10	6.80	1.569	1.298	1.952	0.809
7	10	7.10	1.863	1.153	2.093	0.809

The action items performed to post-process the 81 samples pressed at Cincinnati are:

1) measurement of the part pressing lengths in eight evenly spaced locations, i.e., every 45 degrees around the circumference; 2) measurement of the part diameter dimensions (five values) in the as-pressed condition; and 3) sectioning each individual part into many pieces (only 3 parts from each set). Sections were made in the vertical and horizontal planes. A band saw was recently purchased at CAVS to perform the cutting between columns. The goal of this sectioning is to produce a very accurate density map measuring the sectional density of the parts by the immersion method (Archimede's principle). X-ray tomography mapping and micro-hardness testing will also be conducted on some other parts from each set. The remaining parts will be used for the sintering experiments to measure the shrinkage and the dimensional changes.

Constitutive Modeling of Compaction

The finite-element method is an efficient numerical tool to improve the fundamental understanding of the mechanics of compaction and to develop appropriate constitutive laws in terms of the evolution of suitable state variables for the full range of possible compaction mechanisms. It is a complementary technique to characterize the material parameters when measured data are not

consistent from a testing point of view [Sinka et al., 2001.]. By using the inverse method to match the experimental results, the finite-element method can provide a consistent calibration of material parameters.

After the development of the implementation of a constitutive model for powder compaction based on a Modified Drucker/Prager Cap model, which was implemented in ABAQUS/Explicit via the user material subroutine VUMAT, three simulations describing closed-die compaction of cylindrical parts were performed to validate the model. The numerical results were compared to three round samples compacted at Penn State University of final average densities 7.17 g/cc, 7.14 g/cc and 7.20 g/cc using powder III, and of respective final heights 0.2405 in., 0.4445 in. and 0.7780 in. (see above section). Simulations were made using axisymmetric elements (CAX4R with reduced integration) and a symmetry plane was assumed; therefore, only a quarter of the part was meshed. In this comparison between numerical results and experimental data, we looked at the force-displacement of the upper punch and the density distribution, which was compared to the final average density of compacted samples.

Because not all of the density-dependent parameters were able to be characterized, such as the evolution

of the interparticle friction, the cohesion, the cap eccentricity, and the elastic properties, some data were used from the literature [Coube and Riedel, 2001; Wikman, 2001].

In the literature, people found that the die-wall friction is a function of the powder density. The measured friction coefficients range from about 0.2 at high densities to 0.8 or even higher at low densities [Wilkman, 2001, Coube and Riedel, 2001]. Therefore, the die-wall friction is also chosen as constant and its value is $\mu=0.2$ throughout the analysis (which corresponds to the friction value when the force applied to the punch is very high). For the Young's modulus, its evolution is exponential with the density [Pavier and Doremus, 1999]. Here we assumed that the Young's modulus value at full density (7.85g/cc) should be equal to that of a dense steel material, which is 200 GPa.

The tap density provided by the supplier (3.02 g/cc) and the final density were used to estimate the initial fill depth and the course of upper punch assuming there is no die deflection.

Figure 6 shows the density distribution of the three samples at the end of the simulation. We can observe the gradient of density along the die wall due to the friction. In the center of the part, the densities are homogeneous and the density values are very close to the average measured densities, which are 7.17 g/cc, 7.14 g/cc and 7.20 g/cc, respectively, for the round samples of height 0.20 in., 0.40 in., and 0.80 in.

In Figure 7, the predicted evolution of the force displacement is compared to experimental data. There is a good agreement for the maximum force value, but the values differ when the force is increasing. This difference is due to the material parameters of the cap hardening, which need to be optimized for a better agreement.

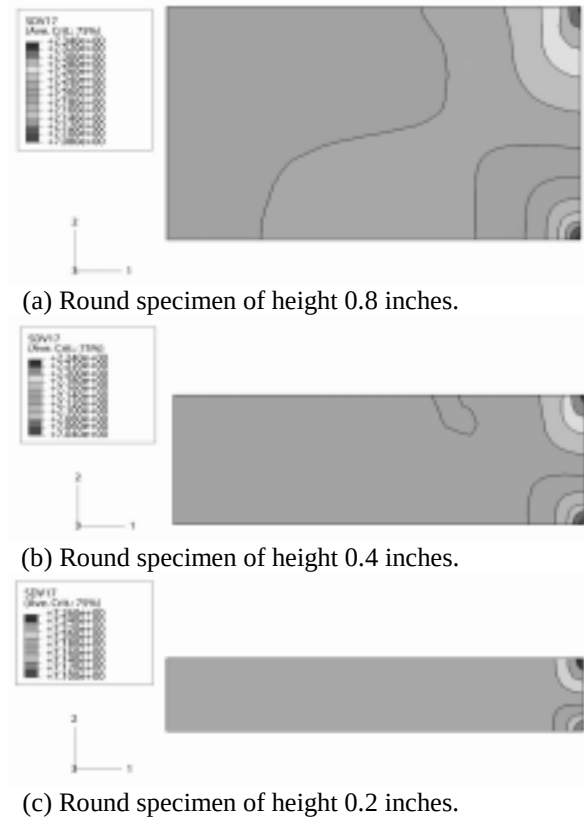


Figure 6. Density distribution for the round cylinders of final height after compaction.

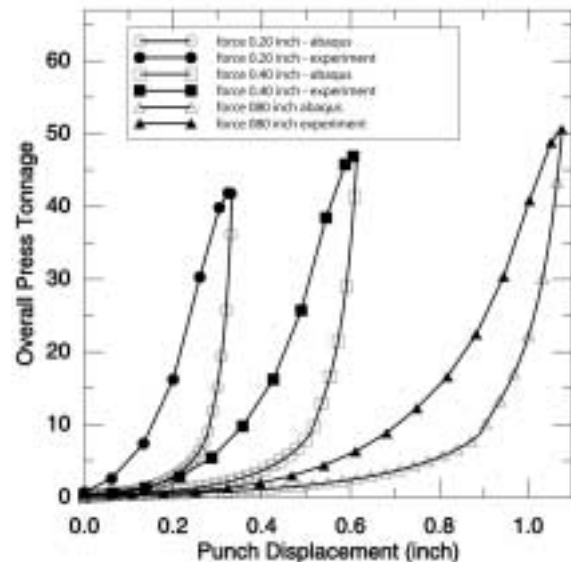


Figure 7. Comparison of the punch force-displacement for the round cylinders of final height 0.20, 0.40 and 0.80 inches.



Figure 8. 3D Density distribution for the round cylinder (0.2 inch final height).

Comparison of Axisymmetric vs. 3D.

The implementation in ABAQUS/Explicit via the user subroutine VUMAT has been done such as it can be generally used for any 3D, plane strain and axisymmetric applications. A closed-die compaction of a cylindrical specimen can be simulated using either 3D or axisymmetric elements. An axisymmetric analysis is much faster and requires less CPU time. A method to validate the 3D implementation is to compare it to the axisymmetric analysis for the same application. Figures 6a, 8 and 9 show a good match between the two analyses. Because the axisymmetric mesh is more refined around the outside diameter, the contour map on Figure 6a shows more contour values.

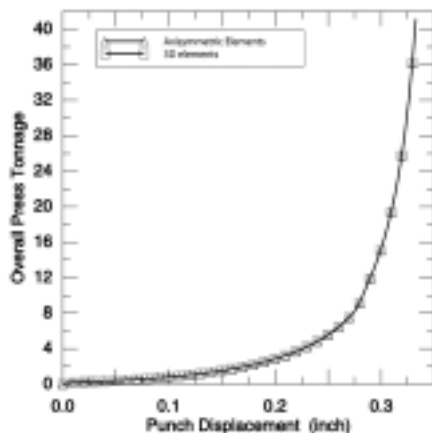


Figure 9. Comparison of the force-displacement using 3D and axisymmetric elements.

Sintering Modeling

An algorithm to implement the sintering constitutive model of Penn State University [McKeeking and Kuhn, 1992; Olevski, 1998] in ABAQUS/Standard was developed based on the stress integration algorithm proposed by Govindarajan and Aravas [1993]. This algorithm will be implemented into the

user material subroutine UMAT to facilitate the transition between the compaction and sintering processes.

Partnership with Metaldyne

In fall 2006, Metaldyne agreed to be our partner and support our modeling effort. Their contribution in this project should be:

Supply CAVS with a large number of "typical" green and sintered parts for validation studies of density distribution and measurement of mechanical and physical property.

Provide powder and test material samples for tension, compression and fatigue tests

Provide information on the process (geometry, load and tool motions) and the performance data of a bearing cap.

Conclusions

The Powder-Metallurgy Performance Modeling of Automotive Components project has mostly completed the modeling of the compaction process. Green round and TRB samples and simple parts have been made and measured for material characterization, parameter calibration and model validation. Further tests and measurements are necessary on these specimens to complete the validation of the constitutive compaction model. Using the new sintering capabilities and equipment at CAVS, these samples will also be tested for validation of the sintering model. After completion of the compaction and sintering modeling, simulations of the main bearing cap will be performed in comparison with the process and performance data provided by Metaldyne. The final objective will be the design, performance and mass optimization of the bearing cap by using lightweight materials such as aluminum and titanium.

Acknowledgements

The authors would like to acknowledge funding from the Center for Advanced Vehicular Systems at Mississippi State University and from USAMP Lightweight Materials Group. We also acknowledge valuable guidance received from William F.

Jandeska (Center for Powder Metallurgy Technology – CPMT) and Scott Burrell (DaimlerChrysler).

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ⁱ Denotes project 410 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.

P. High-Strength Steel Joining Technologies Project (ASP 070ⁱ)

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Contract No.: DE-FC05-02OR22910

Objective

The objective of the High-Strength Steel Joining Technologies project team is to provide welding and joining expertise to the Auto/Steel Partnership (A/SP) lightweighting projects to facilitate the increased use of advanced high-strength steels (AHSS). Additional project objectives include augmenting the technical knowledge pertaining to welding of AHSS through applied research and development of industry standards for quality acceptance and weldability testing of AHSS.

Approach

- Anticipate needs of the A/SP lightweighting projects and conduct applied research to address identified technology gaps.
- Determine welding parameters to produce quality welds, then statically and dynamically test welds produced at these parameters to quantify individual weld structural performance (See Figure 1). Tensile shear strength, impact energy and fatigue life are typically evaluated.
- Utilize commercially-available equipment or equipment typically found in existing manufacturing facilities for AHSS feasibility assessments.
- Focus on materials classified as Group 3 and 4 (see Figure 2), as well as specific materials recommended by the A/SP Lightweight Structures Group.

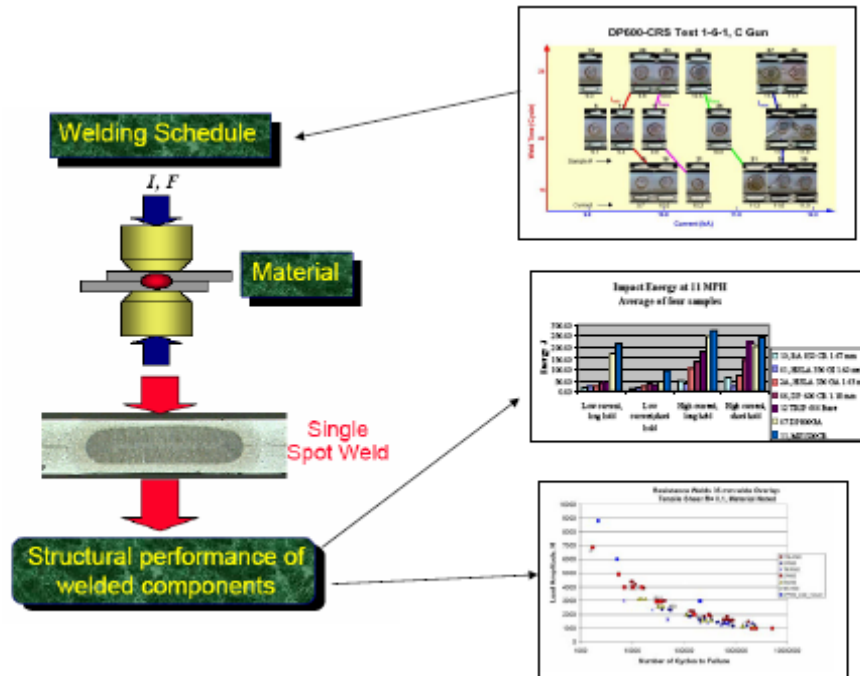


Figure 1. Resistance spot welding.

Group: Tensile Strength (MPa):	1. Low Strength < 350	2. Intermediate Strength 350 – 500	3. High Strength > 500 - 800	4. Ultra High Strength > 800
Typical Materials:	Mild 140YS/270TS BH 180YS/300TS BH 210YS/320TS BH 240YS/340TS	BH 260YS/370TS HSLA 280YS/350TS HSLA 350YS/450TS DP 300YS/500TS	DP 350YS/600TS TRIP 350YS/600TS DP 500YS/800TS TRIP 500YS/800TS CP 700YS/800TS	DP 700YS/1000TS MS950YS/1200TS MS1150YS/1400TS MS 1250YS/1520TS HS 950YS/1300TS
Note: Steels with a minimum tensile strength above 500 MPa (Groups 3 and 4) are generally considered Advanced High Strength Steels (AHSS).				
Source: International Iron and Steel Institute (IISI), <i>Advanced High Strength Steel (AHSS) Application Guidelines</i> , 6 June 2006.				

Figure 2. IISI steel classifications for welding.

- Investigate the use of process finite-element modeling to predict weld quality characteristics and optimize weld process parameters (See Figure 3). Utilize simulation for future projects to develop weld process optimization and weldability assessments. Validate simulation results with experimental data.

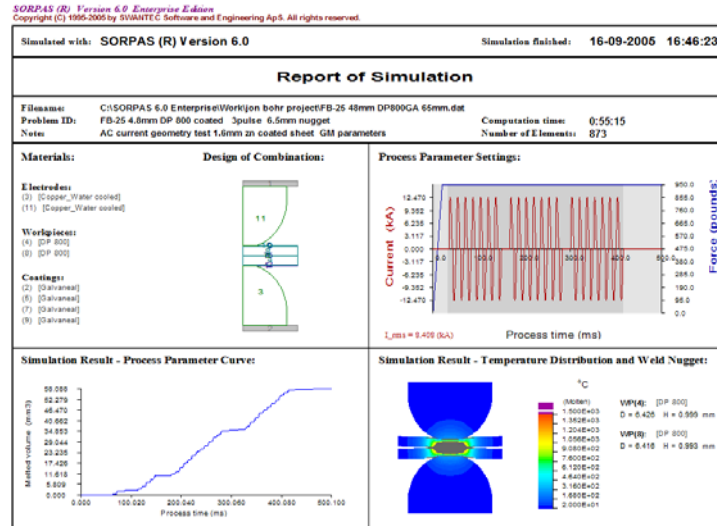


Figure 3. Process simulation report for RSW of DP780 utilizing B-nose electrode and 3-pulse weld schedule.

Recent Accomplishments

- Completed Resistance Welding Project Design of Experiment and report entitled “An Investigation of Resistance Welding Performance of Advanced High-Strength Steels”.
- Completed the test-plan matrix for evaluation of weld processes including MIG, laser-assisted MIG, and plasma-assisted MIG (see Figures 4 and 5). Completed final project report of Structural Weld Sub-Group (SWSG) study.

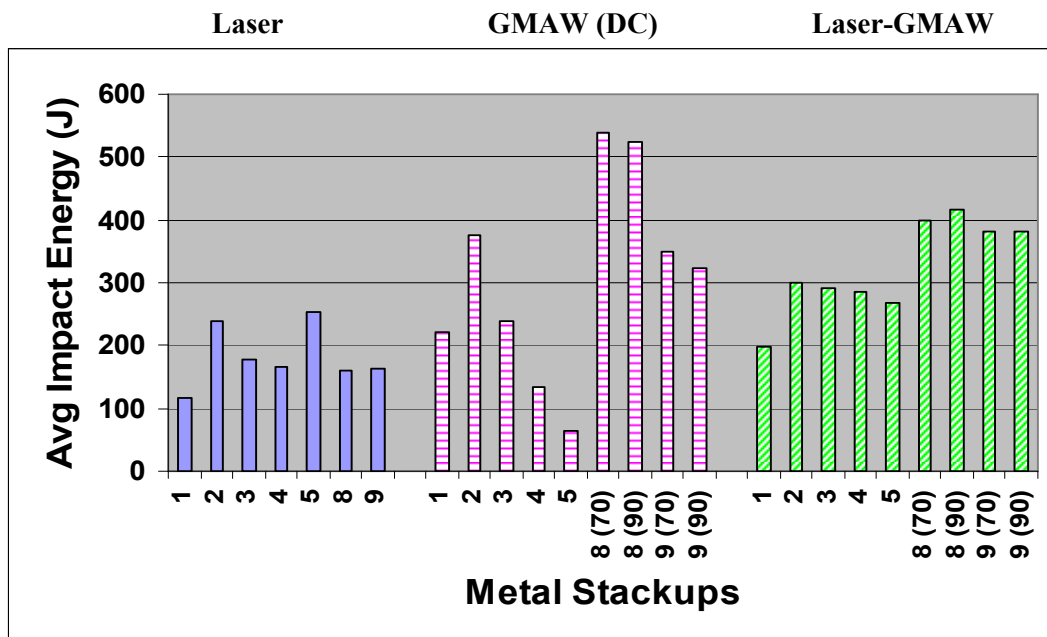


Figure 4. Impact energy comparison.

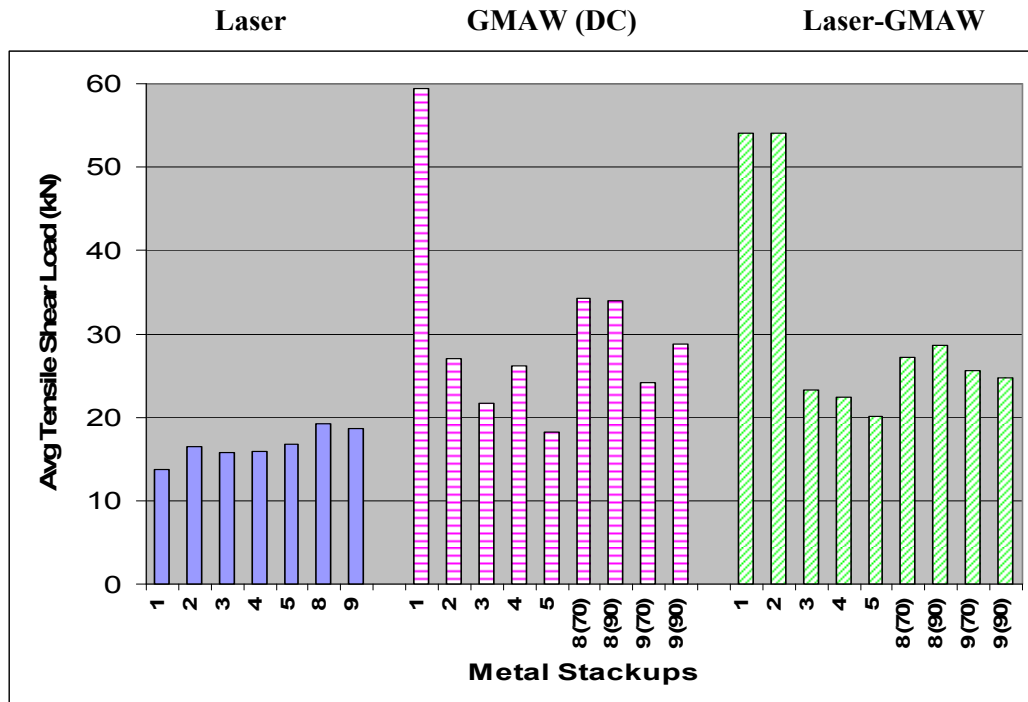


Figure 5. Tensile shear strength comparison.

- Developed weld parameters for specified material grade and thickness combinations for the A/SP Lightweight Rear Chassis Project (see 2.Y), provided technical direction and applied welding practices to fabricate prototype lightweight rear chassis featuring AHSS.
- Produced and tested samples to quantify effect of temperature on impact strength. Completed final project report; “Temperature Effect on Impact Performance of AHSS Welds”. Results presented at the AWS Sheet Metal Welding Conference and International Auto Body Congress.
- Completed projection-weld-fastener resistance-weld process and simulation study. Worked with the University of Waterloo to model the projection welding of a hex-flanged weld nut using SORPAS with a cylindrical block model. Weld test results have correlated with the model. Completed final project report; “Assessing Weldability of Projection Welding Fasteners to AHSS Using Finite Element Analysis”.
- Provided data and post-test samples of tensile shear and impact tests to support development of an automotive industry AHSS resistance-weld quality standard and provided technical support for development of AHSS fracture classification matrix for the standardization effort. (See Figure 6)
- Provide input and materials to Oak Ridge National Laboratory DOE FreedomCAR project on weldability and performance of AHSS in automotive structures (see 5.C).

PROPOSED STANDARD FRACTURE CLASSIFICATION
Submitted to AWS D8 Automotive Standards Committee

WELD FRACTURE CLASSIFICATION							
Fracture Type & Code Number	Weld Fractures - Side View	Weld Fracture Plan View & Code Letter - Bottom Sheet (all may not appear as in side view)					
		A	B	C	D	E	F
1							
2							
3							
4							
5							
6							
7				Not Applicable			
8				Not Applicable			

TWME@DCX.com

FractureD8F+D89Rev7.ppt

Figure 6. Proposed fracture classification matrix.

Future Direction

Future team activities include supporting welding development for the A/SP AHSS Application Guidelines Project Team and developing welding parameter and joint performance data for specific applications on AHSS automotive body prototypes. Future project work also includes:

- Publish the results of the completed project to assess the capability to perform drawn-arc stud welding on AHSS.
- Complete development of a design of experiment (DoE) methodology for material characterization and for assessing manufacturing feasibility of spot-welding AHSS.
- Develop software application to support common deployment and analysis of the AHSS Design of Experiment test method.
- Develop arc-weld procedures for various weld filler metals and AHSS joints, including determining the hot cracking susceptibility and filler-metal compatibility of sheet AHSS materials.
- Complete development of set-up or starting resistance spot-weld schedules and publish the results

Resistance Spot-Weld Project

The purpose of this project is to evaluate the weldability of the new advanced high-strength steels (AHSS) currently being considered by the automotive companies as a solution to lightweighting without compromising cost or structural strength.

The issue facing the producers using resistance welding is to determine if interfacial fracture concerns with lower grades of steel are applicable for AHSS materials. Generally, all standards existing as of 1999 are based on welding of mild steels. The diminished performance of welds exhibiting interfacial fracture was generally accepted for steel grades below 420 MPa. Even in the-low strength materials, interfacial fracture is a common mode when welds are made in thick materials and in structures having mechanically stiff sections. These requirements for lower grades may not apply to AHSS grades.

Objectives

The objective of this work was to characterize AHSS weld properties produced using conventional processes. By reporting these data, designers can determine if the characteristics are suitable for use in specific automotive applications and be assured resistance welds can be produced with conventional production equipment.

1. Develop fracture classifications that can be used to grade welds related to their expected performance based on visual observations of destructive in-process checks.
2. Determine if weld-button pull requirements for lower grades of steel are a relevant strength indicator for resistance welds in AHSS.
3. Document and report all the testing equipment characteristics used to produce the test welds.
4. Report the chemistry and physical characteristics of the base metal actually tested.
5. Determine static and dynamic properties and micro-hardness of welds made using conventional welding processes and standard test methods where they exist.
6. Report fatigue characteristics of welds made with conventional weld practices.

Project Results

1. Based on the test data that evaluated resistance welds using traditional production processes, AHSS materials are higher in static tensile shear strength, higher in impact tensile peak load and energy absorption than the baseline HSLA materials used in this study. AHSS are higher in static and dynamic loading gage-for-gage than DQS and other traditional low-carbon steels with yield strength below approximately 400 MPa.
2. Weld lobes were developed for the range of materials studied in this project. The lobes represent a broad range of values that can be used with conventional automotive welding equipment such as robotic welding, manual welding and machine welding processes.
3. Optimum flat sample width was determined for static and dynamic testing of spot welds to reduce the cost of fabricating special formed channels and using special grippers for the test equipment.
4. Using optimum flat sample width, welds were produced representing largest and smallest acceptable weld size and longest and shortest practical hold times.
5. Tensile shear and impact data were obtained for the range of materials and weld parameters studied in this project using a two-level, two-factor experimental design.
6. A fracture classification matrix was established to enable standardized reporting of qualitative data for destructively-tested welds. This classification matrix is in the process of being adopted by AWS/ANSI.
7. Fatigue performance of resistance spot welds was obtained for all the materials in this project. Fatigue testing was performed at two load ratios, $R=0.1$ and $R=0.3$, for all the AHSS materials in this project and compared to base line materials of DQSK, IF, and HSLA. One additional test using full reverse loading ($R=-1$) was performed to demonstrate the effect of load mode and sample width on fatigue life.
8. AHSS resistance-weld effectiveness was confirmed by applying welding processes developed in this investigation to an AHSS lightweight front structure. This confirmation test demonstrated that the AHSS resistance-

welded assembly performed to engineering requirements with no remarkable weld failures.

The project has been completed and the final report written. An Executive Summary PowerPoint presentation has been prepared and presented to the Joining Technologies Team at large, as well as the A/SP Team.

SWSG MIG/Laser Project (Structural Welding Subgroup)

The arc-welding processes have historically been, and are today, commonly used in the manufacture of automotive structures. Recent increased usage of AHSS in automotive designs initiated a need to evaluate the application of arc-welding processes relative to the joining of AHSS.

This project establishes suitable welding parameters for AHSS material iterations (DP600, DP780, DP800, DP980 and HSLA350). Material section thicknesses ranged from 1.0 mm to 3.4 mm. Five arc-welding processes (GMAW-Pulse/AC, GMAW-Pulse/DC, Laser-GMAW, Laser, and Laser-Plasma) were examined in this operation.

Special consideration was given to the acceptance criteria for this project's welds. The standards of the three OEMs were reviewed and a derivative acceptance standard was established for this study. Hardness/metallographic, impact, and yield/tensile properties related to the resulting weldments are presented as the results of this investigation.

- AHSS materials were successfully joined with the processes studied.
- Weld processes utilizing filler material demonstrated better results than processes with no filler material.
- Laser-welded lap joints generally failed in the weld metal, while GMAW fillet joints generally failed in the heat-affected zone.
- Filler material/electrode strength had no direct effect on the weldment strength.
- Material strength and/or thickness gauge had no influence on laser-welded joint strength.
- Zinc-coated materials demonstrated high levels of porosity without a controlled/ engineered gap.

The project has been completed and the final report written. An Executive Summary PowerPoint presentation has been prepared and presented to the Joining Technologies Team at large, as well as the A/SP Team.

Lightweight Rear Chassis Structures

The Rear Chassis team of the Auto/Steel Partnership needed assistance in welding a lightweight design from Dual-Phase 600, 800, and 980 materials. After obtaining the various materials, the Joining Team proceeded to evaluate the weldability of these materials, and to test weld the combinations prescribed for a rear-end structure. The Joining Team established the weld parameters and assisted the prototype source in making the structure. Weld parameters were delivered to the Rear Structures Team along with mechanical and chemical properties of the test materials.

Low-Temperature Impact Project

To date, performance data have only been reported under ambient temperature conditions, and effects of extreme temperatures on impact of resistance spot welding of AHSS steels have not been considered. This study was focused on the impact performance, through impact energy and peak load of various stack-up combinations of AHSS and mild steels at a large range of possible application temperatures. The conducted experiments provide a better understanding of the effects of extreme cold/hot weather conditions of resistance spot-welded joints. The dynamic responses to low- and high-speed impact loading are investigated, which interact with the effects of stack-ups and temperature. The results show that impact energy and peak load are significantly different in magnitude, trend, and scattering/variation. This study also shows that impact energy is more sensitive to material combinations than peak load.

The project has been completed and the final report written. An Executive Summary PowerPoint presentation has been prepared and presented to the Joining Technologies Team at large, as well as the A/SP Team.

Assessing Weldability of Projection Welding Fasteners Using FEA

While Joining Technology effort has been directed towards resistance spot welding (RSW), little focus has been directed toward projection welding of traditional fasteners to AHSS sheet. Weld schedules and expected weld properties of projection-welded joints between fasteners and AHSS sheet are expected to differ from those in traditional material combinations. The highly alloyed chemistry of AHSS and tailored material properties can result in undesirable properties after these materials are welded. Furthermore, the dissimilar-metal combination that is typical of projection welding of fasteners, adds complexity to the issue as a result of different base-metal properties and weld-metal dilution. In this sense, optimization of the weld process may be difficult as it requires an understanding of the effects of process parameters on the properties of the weld and surrounding base metal.

The projection welding process of an M12/1.75/30 hex-flange 3-projection weld nut to 1.2-mm-thick DP780 HDG AHSS sheet has been modeled using SORPAS. The following conclusions have been drawn:

- A cylindrical-block model is best suited to this application. The axisymmetric geometry assumes one projection that encircles the entire nut resulting in a low current density. The rectangular-block model results in excessive deformation in the nut body and requires reinforcement.
- The modeled results show strong correlation with experimental cross-sections.
- Increasing the weld current results in an increase in weld size.
- Increasing the weld force results in a decrease in weld size.
- Increasing the weld time to 4 cycles results in an increase in weld width, but has little effect on weld height.
- Increasing the weld time beyond 4 cycles has no effect on weld size.
- A peak in power during the first 4 cycles due to contact resistance causes rapid melting and collapse of the projection.

- Decreasing current density after collapse limits further nugget growth.
- Increasing the weld time results in an increase in HAZ size, but can also result in lower cooling rates.
- Modeling and experimental results indicate the projection weld nut in this study to be weldable to DP780 HDG sheet material under various conditions.

The project has been completed and the final report written. An Executive Summary PowerPoint presentation has been prepared and presented to the Joining Technologies Team at large, as well as the A/SP Team.

Conclusions

Additional welding issues will be addressed during 2007 by the Joining Technologies Team, funded by USAMP Lightweighting initiatives and member-company in-kind contributions.

Presentations and Publications

1. Warren Peterson, Edison Welding Institute; Ilaria Accorsi, DaimlerChrysler Corporation; Ted Coon, Ford Motor Company; "Review of Weld Mechanical Property Specification Requirements in AWS D8.1 (Proposed);" Presented at the May 9-12, 2006 American Welding Society Sheet Metal Welding Conference XII in Livonia, Michigan.
2. Amir R. Shayan, Xiao Su, and Hongyan Zhang, University of Toledo; Bipin B. Patel, DaimlerChrysler Corporation; "Temperature Effect on Impact Performance of Advanced High-Strength Steel (AHSS) Welds;" Presented at the May 9-12, 2006 American Welding Society Sheet Metal Welding Conference XII in Livonia, Michigan.
3. Michael L. Kuntz, University of Waterloo; John C. Bohr, General Motors Corporation; "Modeling Projection Welding of Fasteners to AHSS Sheet using Finite-Element Method;" "Presented at the May 9-12, 2006 American Welding Society Sheet Metal Welding Conference XII in Livonia, Michigan.

4. James Dolfi, Dolfi AWS, “An Investigation of Resistance Welding Performance of Advanced High-Strength Steels,” Presented at the September 19-21, 2006 International Auto Body Congress in Novi, Michigan.
5. Michael D’Agostin, RoMan Engineering Services, “Advanced High-Strength Steel (AHSS) Weld Performance Study for Autobody Structural Components.” Presented at the September 19-21, 2006 International Auto Body Congress in Novi, Michigan.
6. Bipin B. Patel, DaimlerChrysler Corporation; Amir R. Shayan, Xiao Su, and Hongyan Zhang, University of Toledo; “Impact Testing of Advanced High-Strength Steel (AHSS) Resistance Spot Welds at Various Temperatures,” Presented at the September 19-21, 2006 International Auto Body Congress in Novi, Michigan.
7. John Bonnen, Ford Motor Company, “Fatigue of Spot Welds in Low Carbon, HSLA, and Advanced High-Strength Steels and Fatigue of Fusion Welds in Advanced High-Strength Steels,” Presented at the September 19-21, 2006 International Auto Body Congress in Novi, Michigan.

ⁱ Denotes project 070 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

Q. Hydroform Materials and Lubricants Project (ASP 060ⁱ)

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Contractor: U.S. Automotive Materials Partnership

Contract No.: DE-FC05-02OR22910

Objective

- Develop mechanical test procedures and forming-limit diagrams for tubes.
- Improve the accuracy and confidence in finite-element modeling of tubular hydroforming.
- Investigate the fabricating and performance characteristics of tailor-welded tubes (TWTs).
- Develop an understanding of steel and lubricant requirements for hydroforming using a combination of experiments and finite-element modeling.
- Support the work of other A/SP project teams when they investigate hydroformed structural components.
- Validate the performance benefits of hydroforming in automotive structures.

Approach

The approach taken on this project is first to gain a basic understanding of the hydroforming process and potential issues, then apply the understanding to support other A/SP project teams in vehicle applications. The investigation encompasses various steel grades and gauges of steel tubing, including TWTs and advanced high strength steel (AHSS) in free-expansion and corner fill processes using several types of lubricants. The work has been divided into several phases.

1. Phase 1 – Investigate free-expansion and corner-fill characteristics.
2. Phase 2 – Investigate effects of pre-bending, lubricants and end feeding on hydroforming limits.
3. Phase 3 – Investigate some of the pre-bending parameters for the hydroforming process.
4. Phase 4 – Investigate some of the bending parameters for AHSS tubing.
5. Phase 5 – Determine the experimental forming limits of steel tubes.
6. Phase 6 – Develop methods for empirical prediction of tube forming-limit diagrams and analysis of hydroforming data.

7. Phase 7 – Investigate tubes made from tailor-welded blanks of varying grades and thicknesses.
 8. Phase 8 – Demonstrate the benefits of tube hydroforming through projects focused on real-world applications.
- Delays in obtaining sheet stock and tubes caused Phases 3 and 4 to follow Phases 5 and 6.

Accomplishments

During the report period (October 1, 2005 – September 30, 2006) the following were accomplished:

- Conducted additional inside and outside corner-fill experiments with 90° bent IF and DP600 tubes with welded end caps to study the effect of elimination of tube end feed.
- Fabricated tubes from tailor-welded blanks of varying thicknesses and grades.
- Conducted free-expansion tests on the above tubes.
- In March 2005 the team was challenged to demonstrate the manufacturability of an advanced high-strength steel (AHSS) hydroform tailor welded tube (TWT) lightweight automotive front rail. The team has taken on this challenge and accomplished the following to date:
 - Procured steels and tooling to fabricate tubes made from tailor-welded blanks with six different thicknesses/grades of high-strength steel.
 - Procured tooling to fabricate the front frame rail from the above tubes.
- Developed a concept for a burst-testing-criteria fixture and identified a contractor to build it.
- Develop a proposal for a project, “Investigation of Fabricating Dual Phase and TRIP Steel Tube from an ERW Production Line.”

Future Direction

During fiscal year 2007, the Hydroforming Materials and Lubricant plans to accomplish the following:

- Fabricate and determine the manufacturing parameters of a hydroformed front frame rail in support of the work performed by Lightweight Front Structures, A/SP 080 (see 2.W).
- Complete laboratory testing of TWTs made from blanks with two grades/thicknesses.
- Conduct free-expansion and straight-tube corner-fill tests on TWTs.
- Complete project on the hydroforming of DP600 and IF Bent Tubes with Welded End Caps.
- Conduct the project, “Investigation of Fabricating Dual Phase and TRIP Steel Tube from an ERW Production Line.”
- Initiate a project to verify yield equations for hydroforming through controlled stress path free-expansion tube testing.

Introduction

Hydroformed steel tubes have been used in the automotive industry to form components that meet structural objectives, particularly strength and rigidity, at optimal mass. One of the most significant advantages of tubes is that they are monolithic closed sections and, as such, exhibit significantly greater stiffness in torsion than conventional open sections, such as “C” and “hat” shapes. Eliminating the need for weld flanges, which are required to join two open members into a closed member, offers a

potential for reducing vehicle mass. The use of hydroformed tubes is limited largely by lack of knowledge of the capabilities and parameters of hydroforming processes and the effects of those processes on the tubes.

This project was undertaken to investigate and quantify the capabilities and parameters of various hydroforming processes so that automotive designers and engineers can utilize a wider range of tube configurations and predict with reasonable accuracy the performance of hydroformed components. Hydroforming tubes made from high-

strength and advanced high-strength steels (AHSS), and particularly tubes made from tailor-welded blanks, are of particular interest because of the potential reduction of mass associated with materials of higher strength and optimal thickness.

Discussion

The Hydroforming Process

Hydroforming is a process in which a tube is placed into a die, shaped to develop the desired configuration of the tube. Water is introduced into the tube under very high pressures, causing the tube to expand into the die. The tube ends can be held

stationary or moved inward during the process to end-feed material into the die cavity.

The process has two distinct stages, shown in Figure 1. The first stage is free expansion, (Figure 1a). It continues until the tube contacts the die wall (Figure 1b). In the second stage, corner filling, the tube is in contact with the surface of the die, which constrains subsequent deformation (Figure 1c). During this stage, the tube expands into the corners of the cavity, accomplishing corner fill. A tube that has been hydroformed is shown with the die in Figure 2. Note that the test was continued until the tube failed.

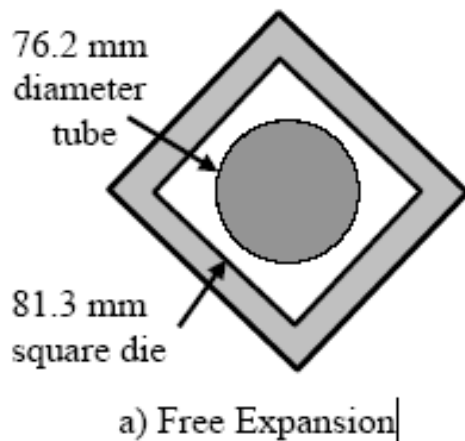


Figure 1a.

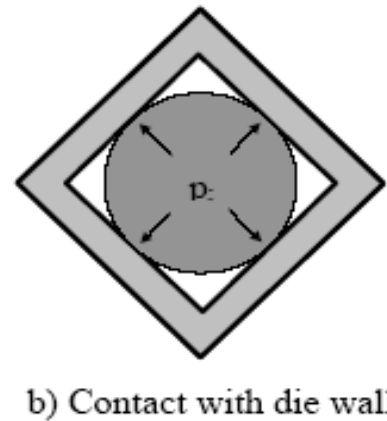


Figure 1b.

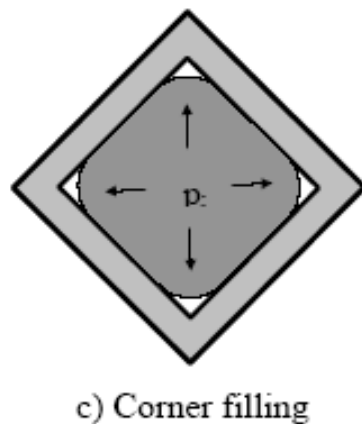


Figure 1c.

The Hydroforming Process.

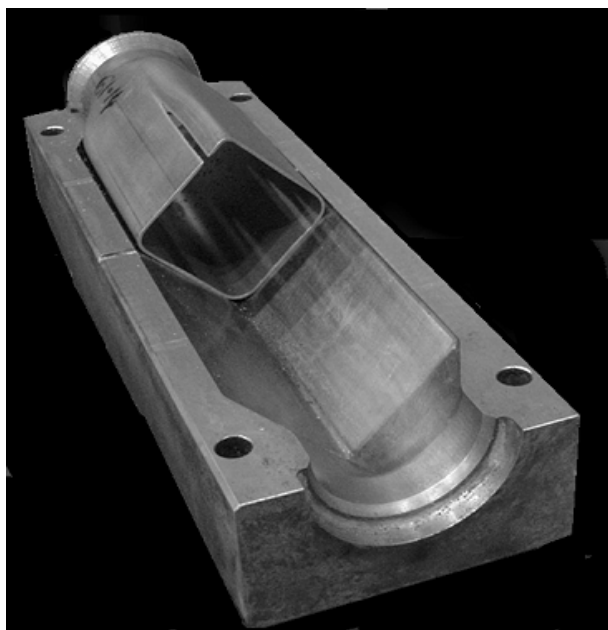


Figure 2. A hydroformed tube and die.

During corner fill, the tube slides against the die; therefore, friction between the tube and die affects the process, and the lubricant used in the process becomes a significant parameter.

Forming-Limit Diagrams (FLD)

During tube fabrication and during both stages of hydroforming, the tube undergoes plastic strain. The amount of plastic strain that can occur before the material fractures is predicted in stamping processes that utilize flat sheet steel by using a forming-limit diagram (FLD). The FLD is determined by the properties of the material. The hydroforming process is preceded by tube-forming and sometimes pre-bending of the tube, both of which induces strains in the material and alters its properties. Before an FLD can be developed for the hydroforming process, the strain history, that is, the strain induced in the material prior to hydroforming must be known.

An FLD is required for any successful computer simulation of hydroforming. Therefore, in addition to experiments with tube expansion to determine the effects of axial compression and tension in combination with internal pressurization, the effects of pre-bending and pre-forming on subsequent formability were addressed. Collected data were used to develop forming limit diagrams for tubular hydroforming of straight tubes. These data will be

used to develop guidelines for optimizing bending operations.

Presently, the formability limits for pre-bent steel in tubular hydroforming are poorly understood. Accuracy needs to be addressed and improved to allow optimum application of tubular hydroforming in the lightweighting of vehicles.

Hydroforming Tailor-Welded Tubes

The project team began work on hydroforming tailor-welded tubes (TWT). The work is being conducted on 76.2-mm (3")-OD tubes made from two material grades and two thicknesses. The test consists of five TWT configurations:

- 1) Baseline: 1.5-mm DP600 single-material tube.
- 2) 1.5-mm DP600 butt-welded to 1.5-mm DP600.
- 3) 1.2-mm DP600 butt-welded to 1.5-mm DP600
- 4) 1.5-mm HSLA350 butt-welded to 1.5-mm DP600
- 5) 1.5-mm HSLA350 butt-welded to 1.2-mm DP600

The blanks were butt-welded before the tubes were formed. In all cases, the tubes are 508 mm (20 inches) long.

The finished tubes were sent to the testing laboratory where they were analyzed. The laboratory found that tube concentricity was not adequate in some cases to allow conventional hydroforming, because it was not possible to maintain an adequate seal between the tube ends and the end caps where water is introduced. At the suggestion of the laboratory, and with the approval of the Hydroforming Team, the laboratory welded the end caps. Free-expansion tests have been completed and the results are being analyzed.

Vehicle Front Structural Rail

In March 2006, the Hydroforming Team began an initiative to fabricate a front structural rail based on a design developed by the Lightweight Front Structures Team (LWFS), ASP080. LWFS had

developed designs for a front rail for two vehicles. The first was the target vehicle. The second had 20% less mass than the target vehicle, which is a reasonable assumption based on anticipated secondary effects resulting in lower mass in systems such as suspension, powertrain and roof structure.

Two design concepts were developed for each vehicle and both concepts were optimized by using tailor-welded blanks. The first design concept in each case requires conventional stamping processes to form a “hat-shaped” member with a “top plate” spot welded at the “hat” section flanges. The second concept utilizes a tailor-welded tube consisting of six different grades/gauges of steel. The tailor-welded tube design did not address attachment to contiguous vehicle components.

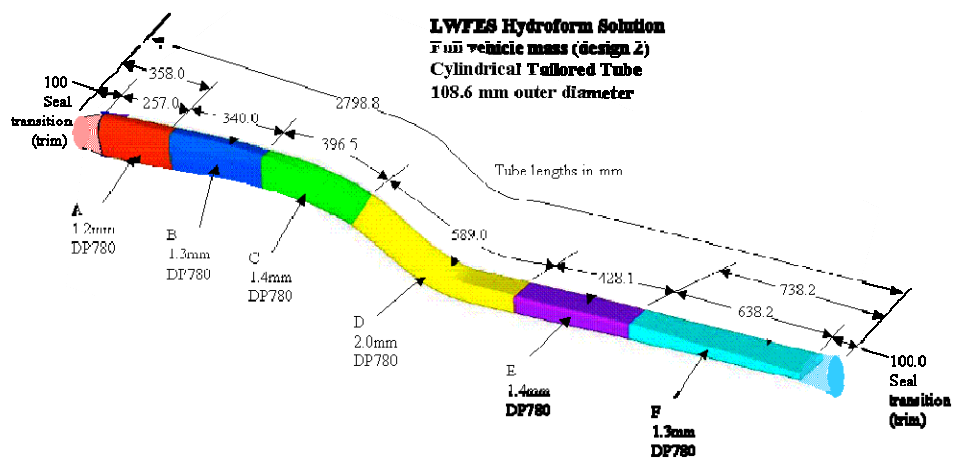


Figure 3. Hydroformed rail for full vehicle mass.

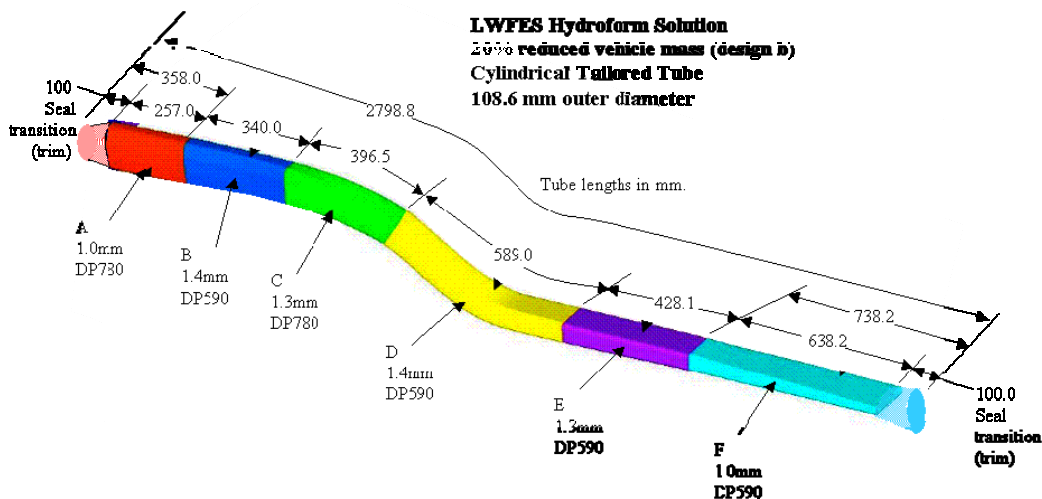


Figure 4. Hydroformed rail for 20% reduced vehicle mass.

The blank lineup for the rail in the target vehicle is shown in Figure 3 and the lineup for the rail in the vehicle with 20% reduced mass rail in Figure 4. It is noteworthy that the rail for the full-mass vehicle utilizes Dual Phase (DP) 780 steel in 1.2-mm to 2.0-mm thickness, while the rail for the 20 % reduced mass vehicle utilizes both DP 780 and DP 590.

The Project Team agreed that the purpose of the front-rail initiative is a manufacturing feasibility study. For this reason, no effort will be made to correct the hydroforming tools to bring the end-product within dimensional tolerance limits. Rather, the hydroforming supplier will be asked to utilize his experience to produce tubes as close as possible to dimensional tolerances, then perform comprehensive dimensional studies on the tubes to learn the effects of the fabrication process, such as springback and die-release.

The Team selected a hydroforming supplier and a tube manufacturer, both of whom have state-of-the-art equipment and expertise, are willing to stretch their current technology and are willing to make significant in-kind contributions to the project.

At the end of this reporting period, the hydroforming tools have been procured, the tube-forming tools have been procured, and fabrication of the tubes is under way.

Burst Criteria

The hydroforming team also recognized the need to develop burst criteria for hydroformed tubes. To date, a test fixture has been prescribed and a vendor has been selected to design and build the fixture. The second phase of this initiative will be the actual tests.

Future Work

During the 2007 fiscal year, the Hydroforming Materials and Lubricants team plans the following work:

1. Continue laboratory analysis and hydroforming tests on TWTs made from two blanks.

2. Manufacture front rails from TWTs to both designs (target vehicle and 20%-reduced-mass vehicle, Figures 3 and 4).
3. Perform analyses on hydroformed rails.
4. Develop burst-test criteria by building a fixture specially designed for the purpose and conducting prescribed tests.
5. Complete project on the hydroforming of DP600 and IF bent tubes with welded end caps.
 - Tube bending speed has only a minor effect on bending strains and subsequent hydroforming; bending radius, however, has a large impact.
 - Lubricant selection is important as it affects bending and hydroforming strains.
 - Tube end feeding is very beneficial for achieving complex geometries.
 - Forming-limit diagrams based on sheet-feeding technology are useful for predicting necking strains in free-expansion hydroforming, but bursting in closed-die hydroforming requires further understanding.
6. Conduct the project, "Investigation of Fabricating Dual Phase and TRIP Steel Tube from an ERW Production Line."
7. Initiate a project to verify yield equations for hydroforming through controlled-stress-path free-expansion tube testing.

Conclusions

Analysis of tests run during this reporting period indicates that:

- Tube bending can significantly limit subsequent tube formability and needs to be accounted for in part design

Presentations and Publications

1. “Hydroforming Group”, Auto/Steel Partnership Program Review, Department of Energy, September 21, 2005.
2. “Hydroforming Committee,” A-S/P SPARC financial planning review, July 18, 2006.

ⁱ Denotes project 060 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

R. Sheet Steel Fatigue Characteristics Project (ASP 160ⁱ)

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Contractor: United States Automotive Materials Partnership

Contract No.: DE-FC05-02OR22910

Objectives

- Compile the test data generated in the previous phases of the program into a user-friendly database that can be used in all phases of design and analysis of sheet-steel-vehicle bodies.
- Investigate the fatigue life of joints formed by spot welding, adhesive bonding and weld bonding (a combination of spot welding and adhesive bonding).
- Explore the fatigue responses of AHSSs after being subjected to metal inert gas (MIG) and laser-welded joining and compare this behavior with that of standard automotive steels.
- Assist the Joining Technology team in identifying the optimum welding parameters for laser- and MIG-welded joints, and develop a fatigue test program.

Approach

- Investigate the fatigue characteristics of resistance spot welding, a fusion process in which the metal pieces to be joined are melted and re-solidified via a brief, high-voltage electrical pulse, forming an alloy with a distinctly different microstructure than that of the parent metals. At the intersection of the weld nugget, or button, and the faying surfaces, a crack-like discontinuity is formed which is often the site of initial crack growth. In addition, the weld nugget itself may contain discontinuities (such as porosity), which can also become sites at which fatigue cracks form. The amount and type of discontinuities and thus the fatigue

properties, can be affected to a considerable extent by the welding process. The microstructures of the joined metals are also changed in the area adjacent to the weld, which is known as the heat-affected zone (HAZ).

- Investigate the fatigue characteristics of adhesive bonding, which substitutes an entirely different material in place of the weld to act as the load-bearing connection. The adhesive must adhere to the metals being joined and resist interfacial fatigue failure at the adhesive/metal interface and within itself (cohesive failure).
- Investigate the fatigue characteristics of weld-bonding, which is a combination of adhesive bonding and spot welding..
- Investigate the previously unknown, or at best little known, factors that are expected either to improve or impact durability, and facilitate their modeling and simulation.
- Reduce the spot-welded adhesively-bonded and weld-bonded test data to a form that is useful to design engineers who perform vehicle structural analysis.
- Develop a test program to investigate the fatigue performance of gas metal arc welding (GMAW) – a fusion-welding process which results in continuous joints. However, under GMAW (or Metal Inert Gas/MIG) welding, a third “filler” metal is introduced under an arc and shielding gas, and, akin to spot-welding, alloys and microstructures are formed which are different from the metals being joined.
- Identify the parameters, including metal grades, metal thicknesses, coatings and joint configurations that impact the fatigue performance of GMAW welded joints.

Accomplishments

- Completed testing of spot-welds in mild steel and ultra-high-strength boron steel, and placed online, the knowledge base developed from the results.
- Developed a specification for fabricating MIG and laser-welded specimens, submitted a request for quotation, selected a contractor and awarded a construction contract.
- Completed fatigue testing of MIG welded specimens created by the Joining Technologies Team, ASP070.

Future Direction

- During the next fiscal year, the project team will complete fabrication of test samples and conduct the first phase of its own program of fatigue testing of metal inert gas (MIG) welds.

Introduction

Future and near-future vehicle designs are faced with several stringent requirements that impose conflicting demands on the vehicle designers. Safety, particularly crash energy management, must be improved while vehicle mass and cost are contained. Advanced high-strength steels, judiciously selected and applied, are currently the best candidates to achieve low-cost (compared with aluminum, magnesium and plastics), reliable materials for meeting these mandates. As structural components are optimized and thinner-gauge, higher-strength materials are assessed, the fatigue life of the areas where loads are transferred become increasingly important considerations. To assess the performance of a component in the design phase, the fatigue characteristics of not only the base material

but the joints, where loads are transferred, must be known. This project has essentially completed testing various grades of steel and steel coupons that have been spot welded, adhesively bonded and weld bonded. Testing of gas metal arc welded (GMAW)- and laser-welded joints is under way.

Discussion

The effort to evaluate the fatigue characteristics of spot welds began in the 2002 fiscal year with presentations by key researchers on the current state of the work at DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. Based on these presentations, the Sheet Steel Fatigue Project Team has produced results beneficial to all three companies. Early in the planning, the Auto/Steel Partnership (A/SP) Joining Technologies

Team was consulted, and that team prepared the samples that were tested. This interaction ensured that the samples were joined using consistent procedures that were properly controlled and in adherence to the best current practices in sheet-metal joining in the automotive industry.

The following fatigue test parameters were agreed upon and carried out:

- Two modes of testing: tensile shear (Figure 1) and coach peel (Figure 2).
- A single thickness (1.6 mm) was selected to ensure that results were comparable between steel grades. A small, second, thinner gage (0.8 mm) was selected for a small satellite study (one AHSS & one HSLA) on the effects of gage thickness on fatigue.
- Because no such data were available for advanced high-strength steels, several grades in this class were tested.
- Testing was done at two R ratios: 0.1 and 0.3. The stress ratio, R, is defined as the ratio of the minimum stress to the maximum stress in the test cycle. Maximum and minimum values are algebraic, with tension designated as positive and compression negative.

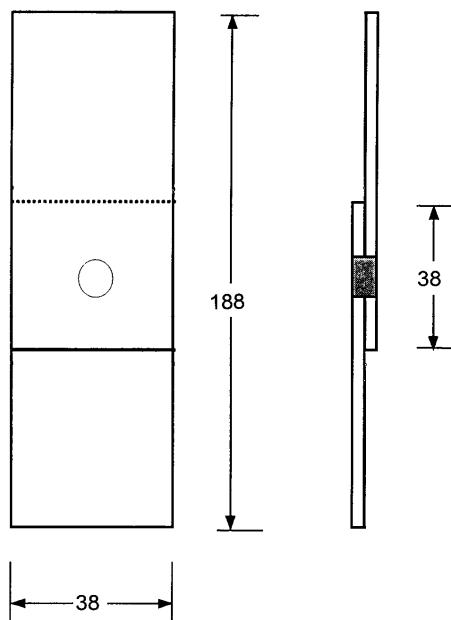


Figure 1. Spot-welded lap shear test specimen.

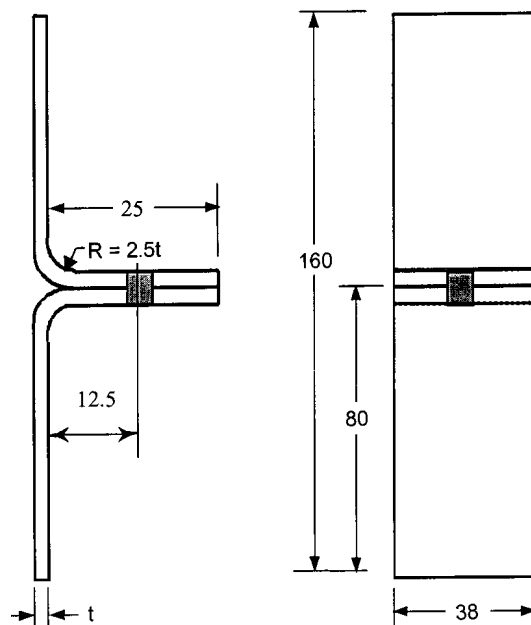


Figure 2. Coach peel test specimen.

- Eleven steel grades were tested.
- While the majority of testing was performed on spot-welded joints, the fatigue performance of adhesively-bonded and weld-bonded joints was explored in several tests series.

Two testing sources, of the nine invited to submit testing proposals, were selected to perform the fatigue experiments: The University of Missouri at Columbia, Missouri, and Westmoreland Mechanical Testing and Research, Inc. in Youngstown, Pennsylvania.

As the testing progressed and results were analyzed, the following tests were added for comparison purposes:

1. Testing at specified R ratios means that the maximum and minimum loads are constant throughout a given test. However, as the maximum load is increased to generate fatigue-curve data, the minimum loads also increase. This process is valuable for establishing baseline data. However, in the real world, load amplitudes can be expected to be variable. For this reason automotive-spectrum load tests, set to two different predetermined scaling, were run.

2. To investigate the effect of button size, fatigue studies were performed on specimens with a welding schedule that produced a smaller weld button.
3. At the request of the Joining Technologies Team, three test series were run using wide samples (125 mm vs. the standard 38 mm). The wider samples minimize rotation of the weld under load and allow negative R-ratios to be explored.

Gas Metal Arc Welded (GMAW) Joints

GMAW welding is the second most common welding process used on vehicle structures, with the rate of applications increasing yearly. GMAW or MIG welds are used not only on body members and sub-frames in passenger cars but also in frames for larger passenger vehicles, light trucks and sport-utility vehicles (SUVs). Therefore, the test samples will be made from two thickness ranges: 1.6 mm for body applications and 3.4 mm for frame applications. These target thicknesses, primarily based on material availability, represent typical as-welded material thicknesses found in body and frame applications respectively.

Frame members do not generally require as much formability as do body members, and they offer excellent opportunities for mass reduction through downgrading. Therefore, tests on frame joints will ultimately employ higher-strength materials than those specific to body members, but often result in similar numbers of welds and amount of weld area.

The Team agreed to four types of testing coupons. Each explores a different loading mode and reveals different information about the material performance: butt weld (Figure 3), single lap-shear (Figure 4), double lap-shear (Figure 5), and perch mount (Figure 6).

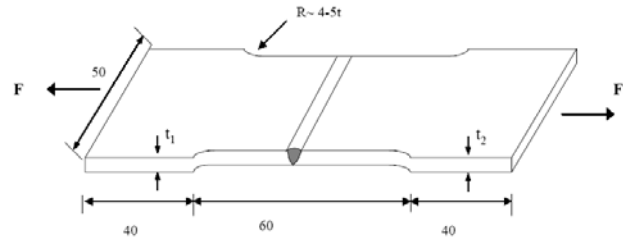


Figure 3. MIG butt-welded specimen.

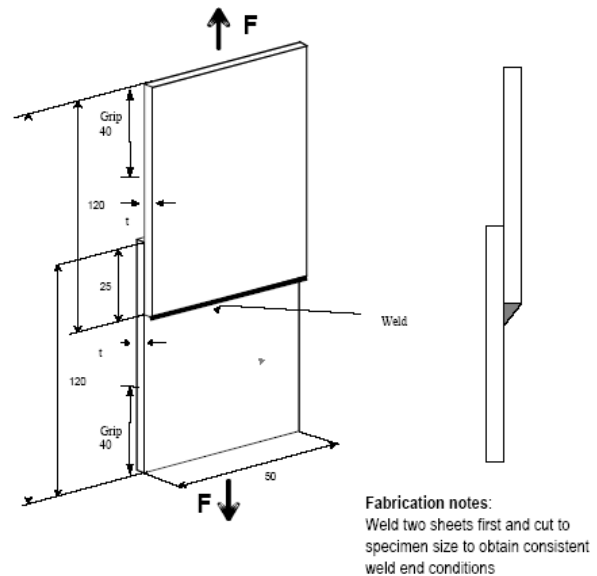


Figure 4. MIG welded single-lap shear specimen.

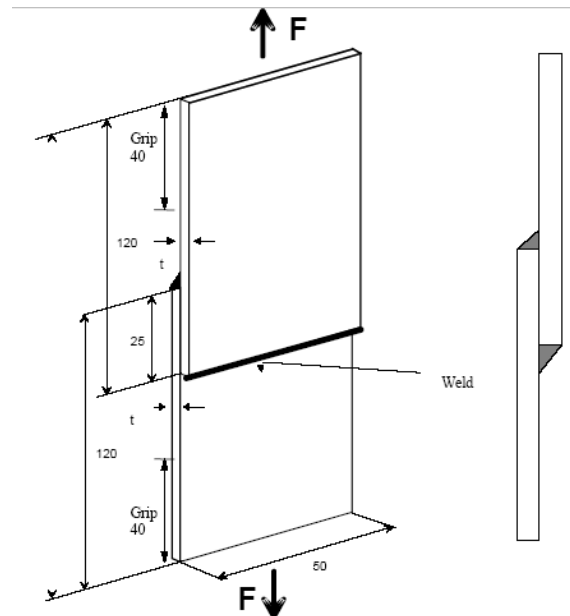


Figure 5. MIG welded double-lap shear specimen.

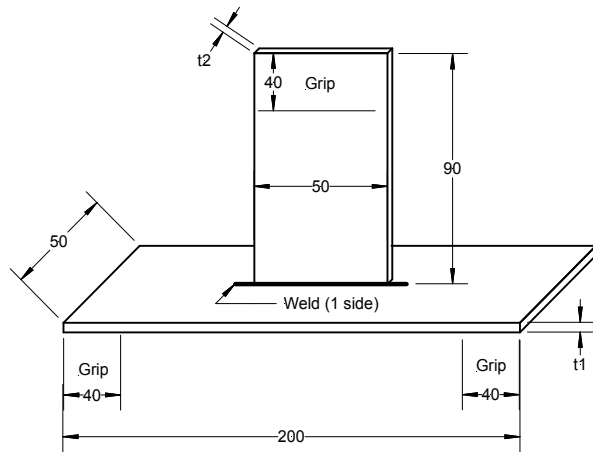


Figure 6. MIG welded perch mount specimen.

Results – Spot welds

Plotted in Figure 7 are all the tensile shear and coach-peel fatigue results for all nominal 1.6 mm gage materials with 7 mm-diameter spot weld, conventional steels and AHSS included. Data labels ending in R0.1 indicate R=0.1 loading and data labels ending R0.3 indicate R=0.3 loading. Run outs are plotted but not otherwise indicated in this figure.

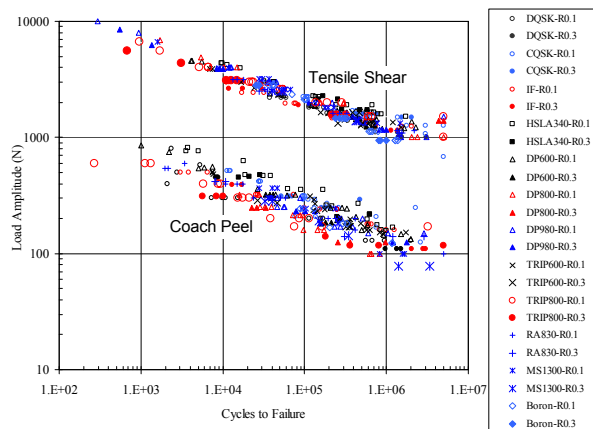


Figure 7. Fatigue results for all 1.6-mm-thick, 7 mm diameter nugget spot-welded materials.

Two thicknesses of HSLA340 (1.0 mm and 1.78 mm) and two thicknesses of DP600 (1.53 mm and 0.83 mm) are compared in Figure 8. The nominal button size for all specimens was 7.0 mm, and the welding parameters were held as similar as possible between the gages/grades without compromising strength. It was expected that the

thinner gages would show shorter life because of the intrinsically higher stresses in the joint, and this result was indeed found in both materials.

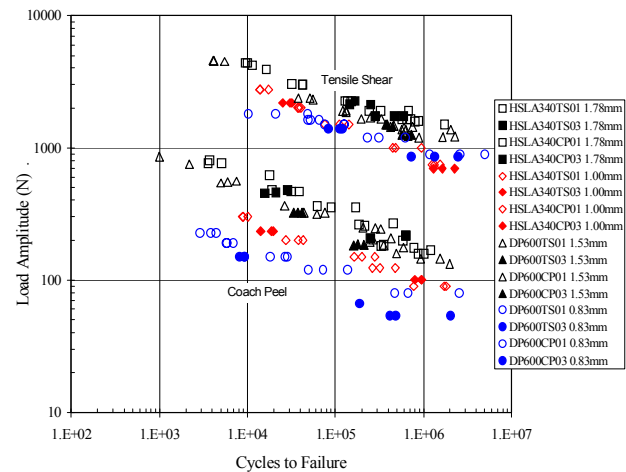


Figure 8. Effect of thickness on fatigue performance.

Results – Fusion Welds

Fatigue testing of specimens containing the fusion weld-line within the width of the specimen was conducted to assist the Joining Technology team in identifying the optimum welding parameters for laser- and MIG-welded joints. The dimensions of the specimens are shown in Figure 9. The weld location was centered between the edges of the sample and the robot travel was 25 mm total. This produced a weld with a start and a stop within the gage section of each specimen. GMAW welding of the DP780 AHSS was performed with 70 ski and 90 ski filler wires while GMAW welding of the DP600 AHSS was performed with only 70 ski filler wire. No filler was used with the laser welds.

The DP600 results of the fatigue, shown in Figure 10A, indicate no significant difference in performance between the AC, DC or laser-assisted GMAW welding processes. Similarly, the performance of the DP780 GMAW welds (Figure 10C) was not influenced by either the process type or the strength of the filler material used. Similar observations may be made concerning the laser processing presented in Figures 10B and 10D. The mean stress appears to be an insignificant factor in the fatigue performance of fusion-welded joints. This behavior can be seen in all the graphs in Figure 10.

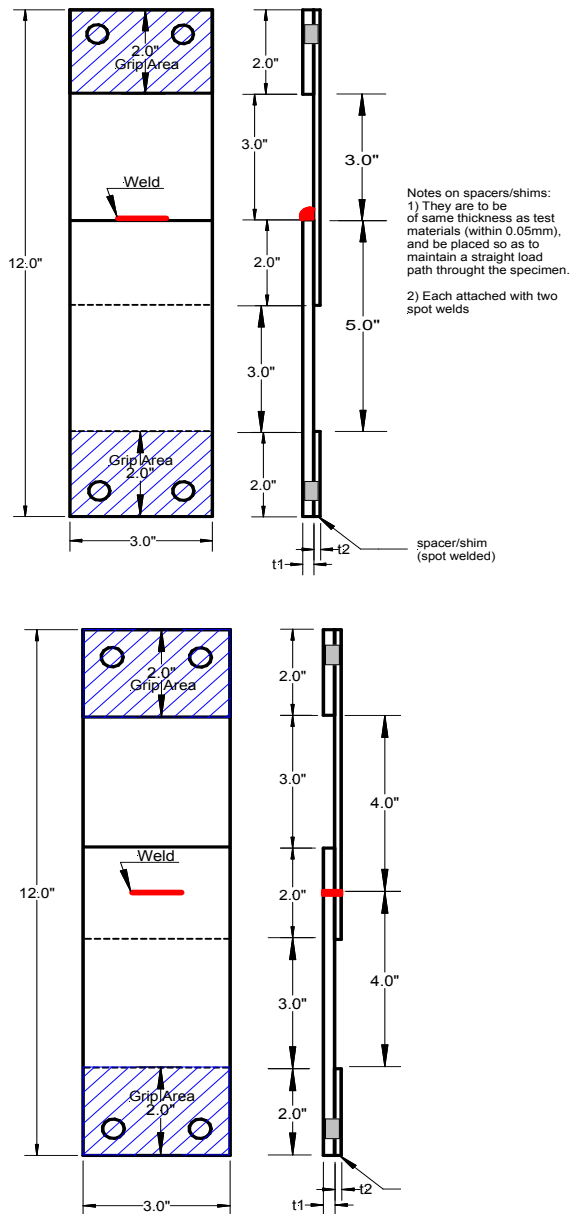


Figure 9. Schematic of specimens for a) GMAW and b) Laser weld fatigue tests. Dimensions in mm.

Conclusions

Analysis of test results indicates that the fatigue performance of a spot weld is independent of the materials being welded. This finding supports the initial understanding that the melting and resolidifying processes associated with spot welding form new alloys and make the properties and coating of the material(s) being joined, and the welding

parameters, insignificant contributors to fatigue performance.

Similarly, the results clearly indicate that, within either the GMAW or laser-weld groups, the type of weld does not seem to influence (e.g., for GMAW it does not matter if the weld is AC, DC, or laser-assisted) the fatigue performance.

Presentations and Publications

1. "Sheet Steel Fatigue Group", Auto/Steel Partnership Program Review, Department of Energy, September 21, 2005.
2. "A/SP Sheet Steel Fatigue Committee," Joint Policy Board, Feb. 1, 2006.
3. J.J.F. Bonnen, Hari Agrawal, Mark A. Amaya, Raj Mohan Iyengar, HongTae Kang, A. K. Khosrovaneh, Todd M. Link, Hua Chu Shih, Matt Walp, Benda Yan, "Fatigue of Advanced High Strength Steel Spot Welds," 2006, Society of Automotive Engineers, SAE-2006-01-0978, pp. 19. *Republished in 2006 SAE Transactions.*
4. Kang, HongTae, "Evaluation of Spot Weld Fatigue Damage Parameters" 2006, Society of Automotive Engineers, SAE-2006-01-0978, pp. 19. *Republished in 2006 SAE Transactions.*
5. "Spot Welds, MIG Welds and their effect on the fatigue of AHSS steels," Mar. 10, 2006 (A/SP Frame group).
6. "Sheet Steel Fatigue Committee," A-S/P SPARC financial planning review, July 18, 2006.
7. "Spot Welds, MIG Welds and their effect on the fatigue of AHSS steels," Mar. 10, 2006 (Joining group)
8. "Fatigue of MIG Welds" AISI Wheel Task force meeting, Nov 18, 2005.
9. ASP Team Review, Dec. 15, 2005.

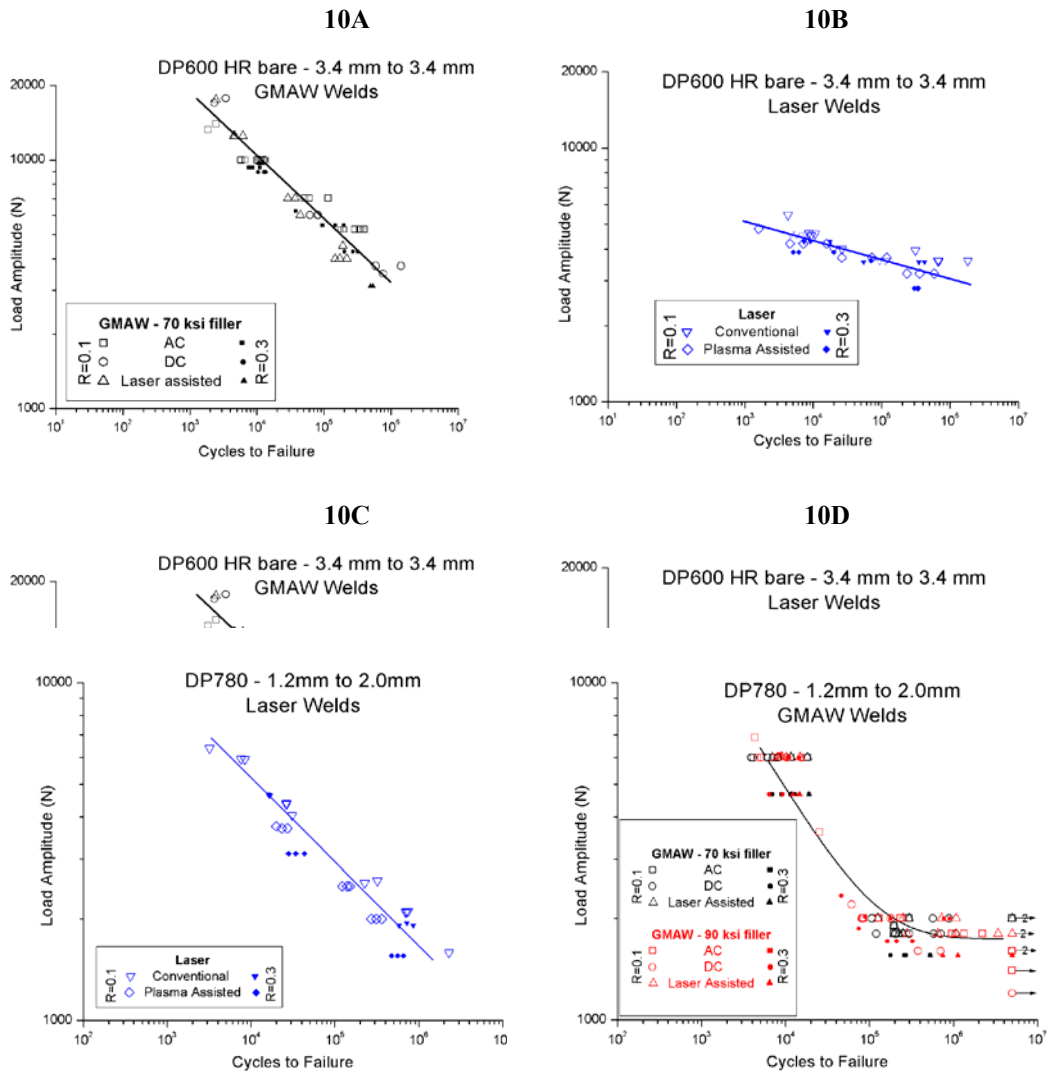


Figure 10. Fatigue performance evaluation of GMAW and laser welds in two advanced high-strength steels, DP600 hot-rolled, bare, and DP780 coated. Specimens for DP600 are 3.4 mm to 3.4 mm while the specimens for DP780 are 1.2 mm to 2.0 mm.

10. "Fatigue of AHSS SpotWelds," 2nd Annual Ford AHSS Conference, Oct. 18, 2005.
11. J.J.F. Bonnen and R. Mohan-Iyengar, "Fatigue of Spot Welds in Low-Carbon, High-Strength Low-Alloy, and Advanced High-Strength Steels and Fatigue of Fusion Welds in Advanced High-Strength Steels," 2006 Proceedings of the International Automotive Body Congress (IABC 2006), pp 12, 2006.

ⁱ Denotes project 160 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

S. Tribology (ASP 230ⁱ)

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Contractor: U.S. Automotive Materials Partnership

Contract No.: DE-FC05-02OR22910

Objectives

- Conduct stamping simulation tests to study the effects of tribological conditions on the stamping performance of advanced high strength steels (AHSS). Stamping performance in this project is defined as minimizing die wear and identifying the optimum die materials and lubricants for AHSS.
- Include these ultimate benefits:
 - Improve test procedure to simulate die wear.
 - Define a model for prediction of die wear.
 - Optimize lubricant/die combinations for AHSS.
 - Maintain common lubricants among automotive companies and steel suppliers.

Approach

- Examine wear rates of different die materials, die-surface treatments and lubricants with advanced high-strength steels.
- Comparison of wear rates with different lubricants and die materials.
- Evaluation of methods of improving die life.
- Optimized lubricants/die combinations for advanced high-strength steel.
- Project consisting of L16 (DoE) two material grades, two thickness, two sheet coatings, two bead radii, two lubricants and two bead coatings.

Accomplishments

- Completed Phase 1 report “Enhanced Stamping Performance of High Strength Steels with Tribology.”
- Completed Phase 2 report “Effect of Stroke Length and Penetration on Die Wear.”
- Obtained steel coils of galvanized & galvanized HSLA340 and DP600 supplied by partner companies.
- The material is used in the wear tests for Phase 3.
- Collected data for the eight test conditions.
- Completed Phase 3 report “Enhanced Stamping Performance of High Strength Steels with Tribology – Report on Phase 3 Testing.”

Future Direction

- Develop wear rate model to predict die life.
- Gather wear test data to substantiate model.
- Correlate model with production data as AHSSs come into production.

Progress Report

October 1, 2005 to September 30, 2006:

A project was initiated to improve the understanding of the effects of lubricants on die wear and part dimensional variation (springback due to interfacial friction) associated with stamping of high-strength steels. Die material will also be studied. Advanced high-strength steels (AHSS) may require different lubricant and/or die material to minimize die wear, achieve consistent friction, and reduce part variation.

Improving the Life of High-Strength Steel Stamping Dies:

Executive summary:

The scope and objectives of this study grew out of previous work of the Auto/Steel Partnership Tribology Team. Findings in Phase 1 (2002) and Phase 2 (2003) of this project highlighted potential issues with the stamping of AHSS. Drawbead tests revealed much higher restraining forces and evaluated temperatures with DP600 over AKDQ and HSLA steels. How would the higher contact stress and elevated part temperature associated with AHSS effect die life? How would part geometry be affected? What process changes such as lubricants and die treatments can be used to increase die life and improve process capability? Phase 3 (2005) investigated the differences between AKDQ, HSLA and DP600 steels with respect to die temperature and restraining force on die wear test. Phase 3

results showed that factors other than sheet strength were important in determining heat transfer to the dies. Also, restraining force decreases with the number of parts produced.

The Die Wear Test was developed by TribSys Inc. to measure die wear at production volumes and rates. Earlier studies had been limited to 12,000 parts. The Phase 4 plan was to study wear with AHSS in the forming of 48,000 parts for 16 different test conditions (a total of 768,000 parts).

The tests were run over a period of three months at production rates averaging 15,000 per day. Data were collected and analyzed using software specifically designed for this experiment.

Statistical analysis of the data shows that that restraining force or stress is most influenced by the sheet thickness and bead radius. Surprisingly, sheet coating was also found to be a significant factor. Thinning strains measured on the collected samples throughout the test confirm these results. One significant result was the difference between HSLA and DP600 increases as sheet thickness increases.

Wear-volume measurements show both abrasive and adhesive wear. The type of wear was generally related to the type of bead coating. In general, adhesion was heaviest with the galvanized sheet while abrasion was heaviest with the galvanized sheet. The effect of wear on restraining force and

thinning strain was not directly related to one type of wear but more on the nature of the worn surface.

The run-in period for each test was analyzed and revealed that the harder, more abrasive GA coating achieved a stable restraining force sooner than the softer GI coating. In addition, the CrN coating had a much shorter run-in period than the uncoated D2 for most conditions.

The final report along with conclusions is not yet completed.

Other Technical Papers:

Five (5) technical papers on the results of Phases 1, 2 & 3 are being written.

1. Characterizing Automotive Sheet Steel & Lubricants.
2. Temperature Effects with Film Lubricants in Stamping AHSS.
3. Comparison of Mill Applied Lubricants on AHSS using Draw Bead Simulator and Twist Compression Test.
4. Sensitivity of Zinc Coatings on Stampings.
5. Effects of Penetration and Stroke Length on DBW Patterns.

Trim Die Wear Study: A Trim Die Wear study was conducted on prestrained, advanced high-strength steels to evaluate wear rates with two materials AISI A2 and AISI S7 with the goal of comparing trim die suitability of these two die materials.

The use of advanced high strength steels (AHSS) and ultra high strength steels (UHSS) is steadily increasing in the automotive industry. There are anecdotal reports that these steels are causing trim dies to wear out prematurely [1]. Trimming processes are used to remove excess sheet metal from stamped parts and are a crucial factor for assembly and overall dimensional quality.

Tribological experiments are helpful in developing an understanding of the effects of the accelerated wear associated with the processing of AHSS. These experiments can determine the type of wear the tool steel will be subjected to such as face wear, flank wear, or edge wear (Figure 1[2]).

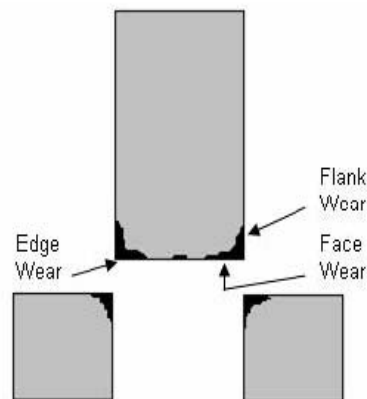


Figure 1. Types of punch/die wear.

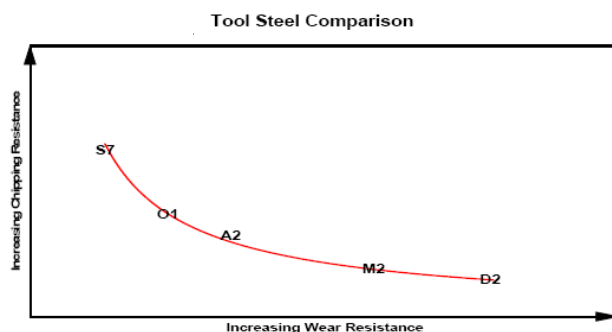


Figure 2. Tool steel comparison chart.

There are many variables in trimming that can affect die life. These variables, related to tool materials, lubricants, and sheet can be studied in controlled experiments to better understand their influence on the trimming process. [2].

In this study, we examined the effect of tool materials on trim die life. Two common trim die materials were chosen to represent current industrial practice for wear and chipping resistance (Figure 3). The intent of this study was to establish a die-wear baseline with pre-strained AHSS material, whereas previous studies have examined die life with unstrained (as received) material [3]. Testing the material in the pre-strained form should improve the accuracy and relevance of the study for the stamping industry.

Experimental Methodology

Experimental Design: The study of trim die materials was run concurrently with a larger experiment where eight different sheet steels were

- 44 kN Hold down
- Clearance = 0.05t
- Die Width = 19mm
- Straight Cut
- Square ground edge

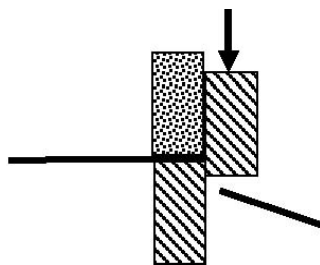


Figure 3. Setup.

tested in a coil-fed drawbead simulator. The trim dies were designed to be changeable half-way through the experiment without disrupting the drawbead simulator setup. The sheet steel tests were split up evenly, so that each of the two trim die sets saw the same material type and thickness. By the end of the test, the S7 and A2 trim dies had each made a total of 384,000 cuts.

Die Materials: Two widely used tool steels, AISI A2 and AISI S7, were selected for this experiment [4]. These tool steels were machined and hardened to specification by a local heat treating company [5]. The trim dies were ground parallel to the trimming edge of the die; while this is not the optimal orientation for grinding dies (parallel to punch movement is recommended [6]), it is common practice and should represent a worst case scenario. The sharp right angle produced on the die edge by grinding was not beveled in any way prior to testing.

Sheet Materials: Two thicknesses (1.2 mm and 1.6 mm) of DP600 and 340XLF grade steel with galvanneal and galvanized zinc coatings were coil fed into the test apparatus. The 50 mm-wide strips were trimmed after being pre-strained in a drawbead simulator. Thickness strains of the pre-strained sheet ranged from 5.6% to 22.7%. Since the trim die study was run concurrently with the drawbead wear study, there was no attempt to hold the sheet material properties constant. The range of grades, coatings, thicknesses, and strains could be considered at an average to establish the severity of the test conditions for long-term wear effects (abrasive wear). The worst conditions (DP600, 1.6 mm and high strain) established the severity for short-term wear effects (stress cracking).

Equipment Setup: The trim dies were installed to ensure the mating surfaces were clean and free of oil and debris. The trim die clearance was set to 5% of

as received material thickness. This clearance was maintained for the two different sheet materials by adjusting the lower trim die shims. The effective clearance was roughly 7% of the strained materials. The upper trim die was fixed to a hydraulic cylinder, sliding within a confined guiding system. The guides had very tight tolerances that ensured the trimming blades had little or no play. The blades were a straight design with a zero-degree shearing angle; while this maximized cutting force, it made it easier to set the trim die clearance and once again was considered as the more severe condition. This upper moving assembly was regularly greased and cleaned of any debris that may inhibit trimming performance, and the hydraulic cylinder was sized to accommodate the high forces required to shear the strained AHSS.

The die wear tester ran at approximately 30 cycles per minute, where each cycle consisted of a clamp/cut. Material was then pulled through the die; the clamp was released and then returned to the starting point where the cycle was repeated (Figure 3). The only lubrication present was two varieties of mill-applied lubricants, standard rust preventative mill oil and the other, a mill-applied wax. It was felt the small amount of lubricant present would have a negligible effect on the trim die life, since there would be no cooling effect, and there were no EP additives present.

Trimmed material samples were collected throughout the test at 2-hour intervals, which is approximately 3600 cycles. Each sample was labeled with the appropriate test number, time and stroke count. These samples were used for analysis of trim quality. Once all tests were completed, the trim dies were removed, cleaned and set aside for analysis.

Results

Trim Die Condition: The trim dies were inspected for cracking, chipping or any other easily visible wear. Photos and microscopic images were taken of both the upper and lower trim dies. The time of the chipping was traced after testing was completed by examining the edge of the collected samples; thus, the occurrence of chipping is accurate within approximately 3600 cuts.

AISI S7: The S7 die produced the best trim quality and chipping resistance of the two tool steels. The S7 showed no signs of cracking or heavy chipping. The edges of both the upper and lower dies showed very light edge wear (rounding). The S7 die did show heavier signs of face and flank wear easily visible to the naked eye (Figure 4).



Figure 4. S7 lower trim die edge.

Examination of the sheet specimens trimmed with the S7 die showed that trimmed edge quality did not significantly deteriorate from the start to end of the test (Figure 5 and Appendix 2A). There was a slight increase in burr height associate with the rounding of the trim die edge. What appeared to be a small chip on the lower die (see arrow, Figure 4) proved to have been present at the start of testing (as revealed by close examination of the trimmed sheet specimens). It is thought that this small dent occurred during handling prior to the start of the test. The damage area (dent) did not appear to worsen during the 384,000 cuts nor did it seem to have affected trimming performance.

AISI A2: The A2 trim dies did not perform as well as the S7 dies. Sign of flank wear and face wear were minimal, but very heavy chipping occurred at different stages of the test. Approximately 35% of the cutting edge on the lower trim die had been chipped off (Figure 6), leading to a very poor trim quality of the test specimens by the end of the test. The upper portion of the cutter remained intact and showed minimal signs of wear. The differences in wear between the lower trim die and upper trim die can be attributed to reduced stress on the upper cutter (free-end side of the strip).

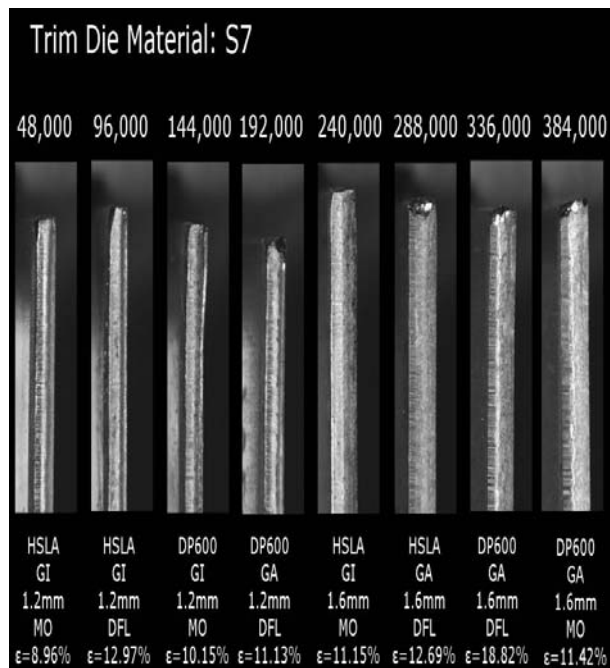


Figure 5. S7 trim specimen edge quality.

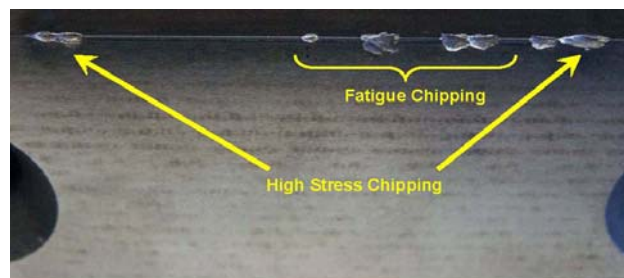


Figure 6. A2 lower trim die edge.

Study of the trim dies and trimmed sheet specimens show that there were two distinctly different types of chipping:

1. Early chipping at the point of contact of the sheet edge.
2. Late test chipping at the midpoint of contact.

The early chipping initiated at the contact with the edge of the sheet is thought to have been caused by the high local stresses (Figure 7). Sheet specimens reveal that this chipping occurred after only

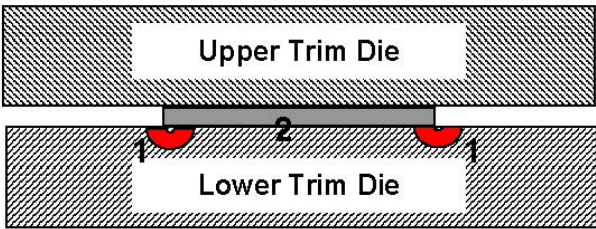


Figure 7. Stress concentration at edge of sheet.

132,760 cuts. The opposite side of die chipped after 235,250 cuts.

The chipping that occurred later in the test started at the midpoint of contact with the sheet was found after 354,900 cuts. It appeared to be unrelated to the earlier chipping at the strip edge. After the first chip was found, others formed rapidly within the final 30,000 cycles. It is likely that the cause of the second type of chipping was cyclic fatigue at moderate stress levels.

Sheet specimens: The chipping did not prevent the trimming of the material, but affected trimmed edge quality (Figure 8 and Appendix 2B). The samples were heavily burred at the corresponding chip location on the die, (Figure 9). The areas which were free of chips, maintained a very good trim quality. Due to the high hardness of the A2 material, the face wear and flank wear were minimal.

Discussion: The A2 and S7 tool steels are commonly used in the metal-forming industry. A2 is roughly 4 HRC higher than S7 in hardness [Appendix 1]; the greater hardness of A2 can be attributed to higher carbon content and the increase in carbides formed. This higher concentration of carbides is the result of

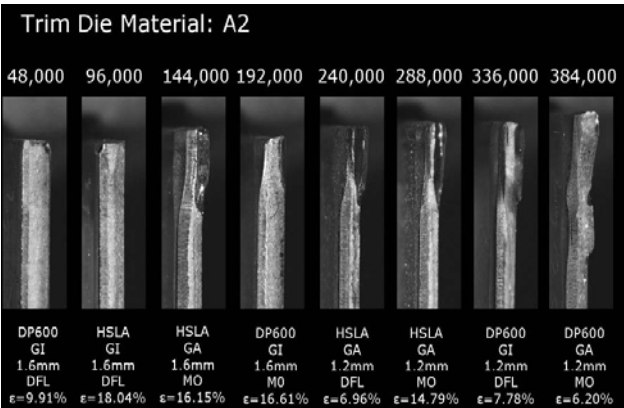


Figure 8. A2 trim specimen edge quality.

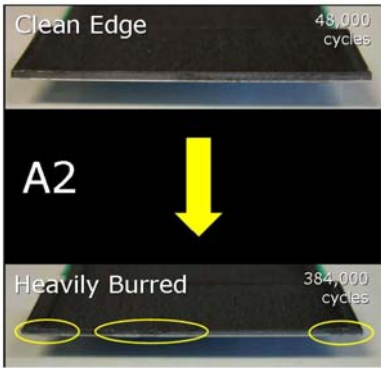


Figure 9. Specimen edge quality on A2.

higher carbon content; greater than 0.5% by weight, and carbide alloying elements such as vanadium, molybdenum and chromium [4]. These stable carbides produce better abrasive wear resistance properties. S7 sacrifices abrasive wear resistance for improved toughness.

Toughness provides resistance to cracking and chipping caused by high local stress (Figure 10). The lower hardness in S7 is responsible for the increased edge; flank and face wear (Figure 11).

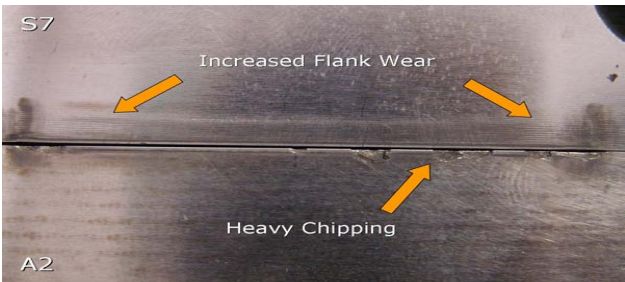


Figure 10. S7 vs. A2 Trim Die Wear.

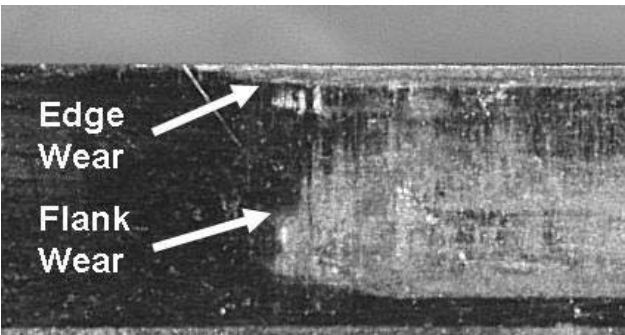


Figure 11. S7 trim die wear.

The wear rates seen in the test simulate what would be seen in an industrial application. The material was pre-strained from 5% up to 20%, resulting in a much harder material to trim than unstrained, as-received sheet.

The sheet edge condition that caused the chipping of the A2 trim die cannot be considered typical of trim dies since trim dies may not encounter sheet edges; however, shearing across a sheet edge is common in blanking dies and is similar to conditions found in trim dies for stampings using tailor welded blanks where a thick sheet is joined to a thinner sheet.

Conclusion

These trim die tests were conducted as part of a larger study and as a consequence each trim die processed a variety of material types, thicknesses and coatings. Each trim die made 384,000 cuts at a rate of approximately 30 parts per minute in prestrained AHSS sheet. It is felt that these conditions are representative of industrial practice.

The comparison of AISI A2 versus AISI S7 tool steels for trimming advanced high-strength steels revealed in the superior performance of the S7 tool steel. Even though the S7 showed a slightly higher abrasive wear rate, it produced excellent trim quality on all material types and thicknesses. No signs of chipping occurred in the S7, whereas the A2 suffered extensively from chipping, even though it had better abrasive wear resistance. Under the conditions that were tested, it can be concluded from this study that S7 would be a better choice for AHSS trim dies particularly applications where a sheet edge causes high local stresses. Further testing involving varying the set clearances of the trim dies for the AHSS may reveal different performance aspects for the two tool steels.

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Schey, J. Tribology of Metalworking, ASM Publication 1983

Skare, T, Krantz, F. Wear and frictional behaviour of high strength steel in stamping monitored by

acoustic emission technique, Wear 255 (2003) 1471-1479, Elsevier Science B.V.

Crucible Tool Steel and Specialty Alloy Information.

Northern Heat Treat Ltd.

Dayton Progress Corporation, private discussions.

Appendix 1 (From Crucible Steel Specifications sheets)

Component	Weight Percent
Carbon, C	1
Chromium, Cr	5.25
Iron, Fe	91.55
Manganese, Mn	0.85
Molybdenum, Mo	1.1
Vanadium, V	0.25

Mechanical Properties

Hardness, Rockwell C	62
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Table I.1 – Crucible AISI A2 chemical composition

Heat Treating Cycle: Austenitizing Temperature/Time /Draw: 1750°F/ 120 min/300°F min [5]

Weight Component Percent Carbon, C 0.55 Chromium, Cr 3.25 Iron, Fe 93.5 Manganese, Mn 0.7 Molybdenum, Mo 1.4 Silicon, Si 0.35 Vanadium, V 0.25

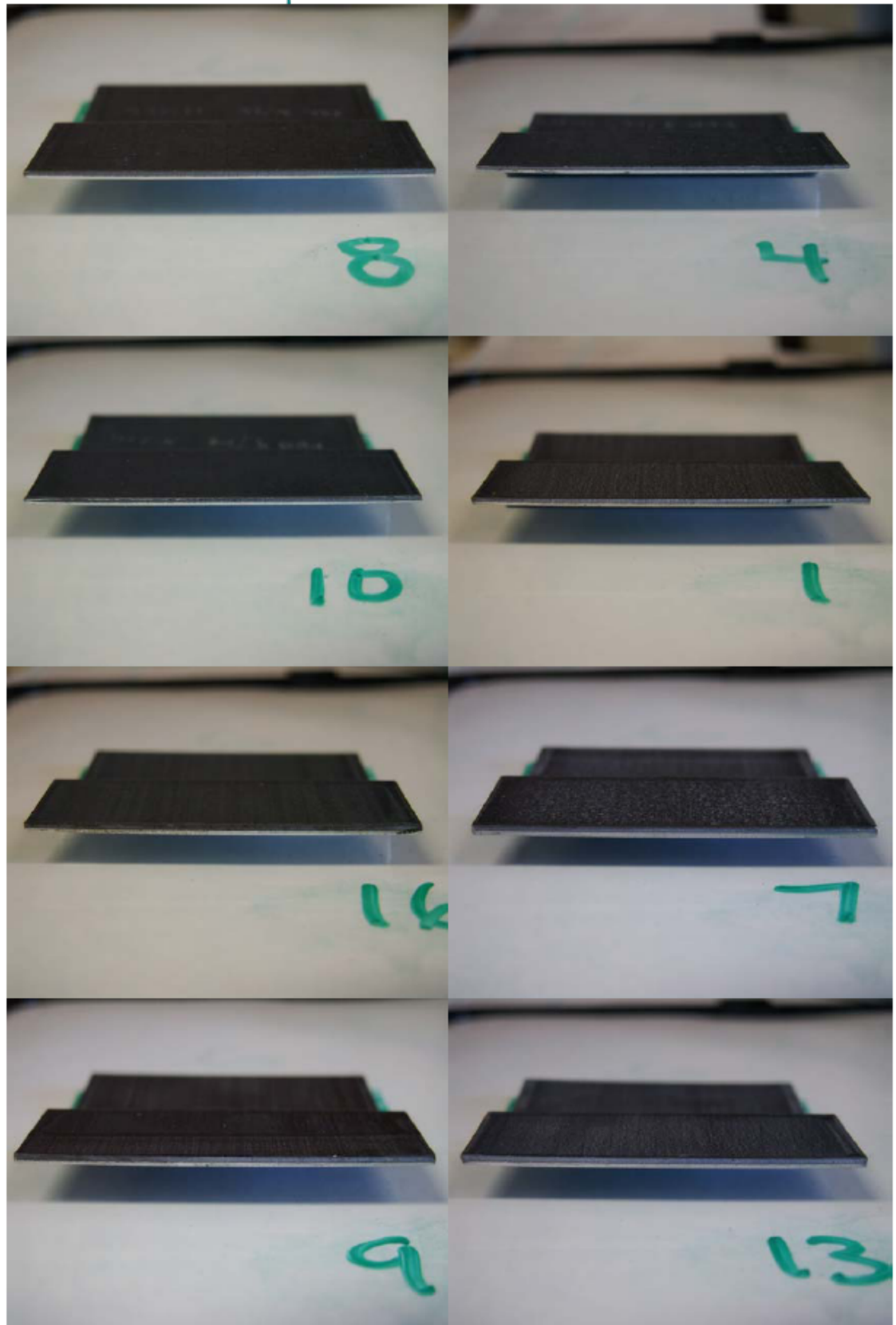
Mechanical Properties

Hardness, Rockwell C 58

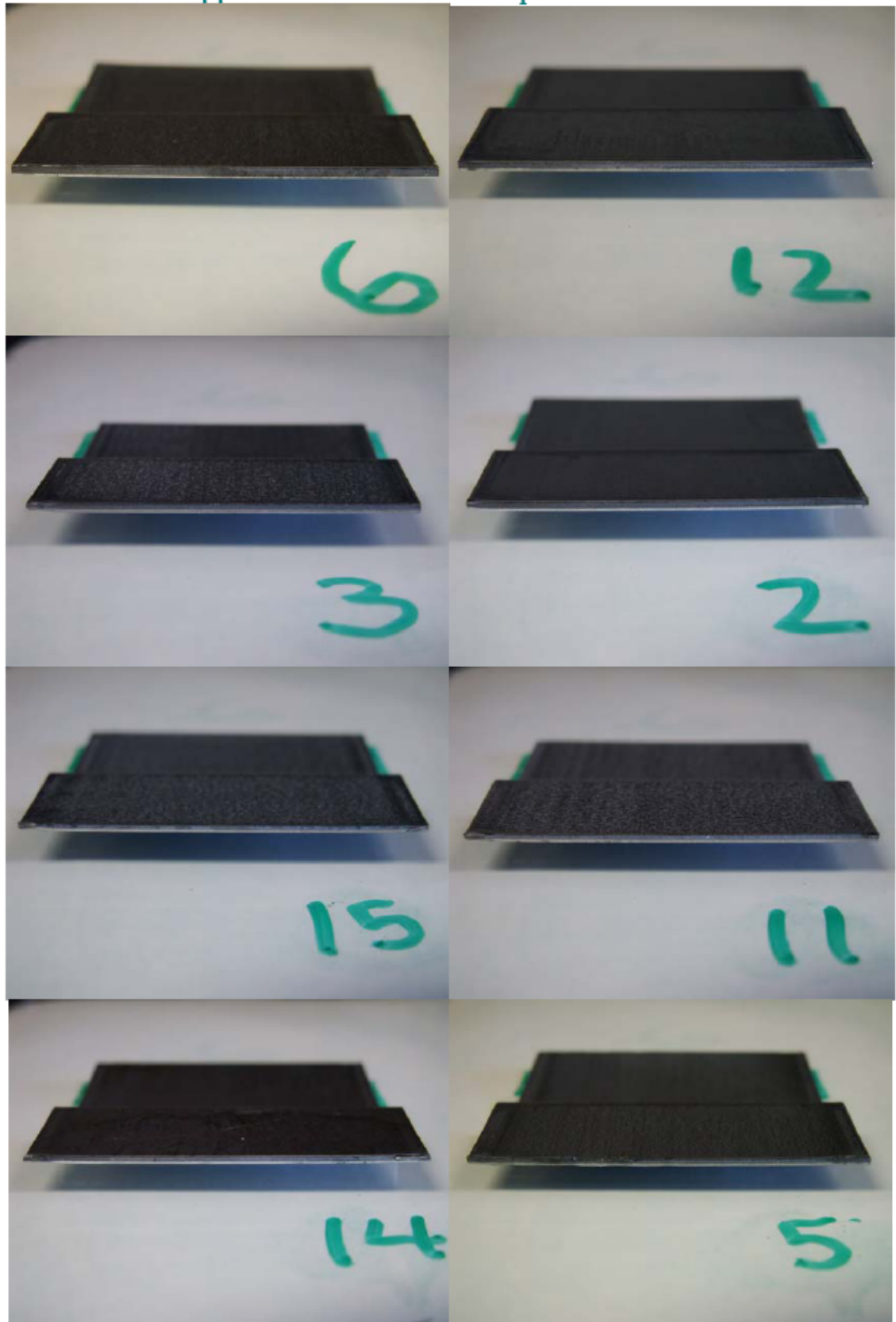
Table I.2 – Crucible AISI S7 chemical composition

Heat Treating Cycle: Austenitizing Temperature/Time/Draw: 1725°F/ 120 min/ 300°F min [5]

Appendix 2A: S7 Trimmed Specimen Pictures



Appendix 2B: A2 Trimmed Specimen Pictures



ⁱ Denotes project 230 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

T. High-Strength Steel Stamping Project (ASP 050ⁱ)

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Contractor: U.S. Automotive Materials Partnership

Contract No.: DE-FC05-95OR22363

Objectives

Determine how to accurately predict and control the amount of springback and other deviations from the desired stamping geometry for parts made from high strength steel (HSS) and Advanced High Strength Steel (AHSS) prior to construction of production tooling.

Develop part design and manufacturing process guidelines that can be recommended to automotive design and manufacturing engineers for the purpose of reducing springback and other part distortions.

Approach

The approach of HSS Stamping Project is twofold:

1. AHSS stamping springback predictability through finite element analysis (FEA).
2. AHSS stamping springback control by developing knowledge of part design geometries that affect flange springback and die processes that control springback.

Several different types of dies have been constructed or are on loan to the Auto/Steel Partnership for the stamping process development.

Accomplishments

Identified additional processes to control springback, sidewall curl and panel twist.

Modified tooling for stretch-forming processes of AHSS auto body structural components to neutralize the residual stresses that cause springback and sidewall curl. Predictable results have been shown for HSLA 350 and DP600 MPa. The tooling was additionally modified for DP780 MPa and DP980 MPa. Panel measurements and data analysis are completed.

Modified panel geometry to show an alternative approach to control springback. Effective use of stiffening beads and other part shape modifications are being recommended to product designers for control of twist, undercrown and springback.

Built new Multi-Process Master Shoe Die and Sub-Die inserts that are capable of a variety of part shapes and processes. The master shoe has a high-pressure hydraulic cushion that can be programmed for various process control features. Sub-die inserts for two Underbody Longitudinal Rails, a Cowl Cross Bar and Body Center Pillar were either built or modified and run in tryout.

Completed three case studies of AHSS part developments by working through the OEMs. Applications guidelines studies were completed on a DaimlerChrysler roof rail reinforcement and on a General Motors and on a Ford Motor Company "B" pillar reinforcement.

Future Direction

Partner companies have observed fractures in parts subjected to stretch flanging or stretching over a die radius. This phenomenon is not currently predictable. For this reason, the project team has solicited, received and evaluated proposals for work in the area of fracture analysis to support future formability analysis in dies. Project work is scheduled for the 2007 fiscal year.

Die trials with the new Multi-Process Die and programmable hydraulic cushion are also continuing. This die is designed as a master die set and pressure system that will accept sub-die inserts to produce a variety of structural parts, such as underbody rails, cross bars and body side-structure pillars. Stamping processes for draw or form die actions can be developed with this tool.

Additional applications guidelines case studies are planned to be completed at the rate of three per quarter by obtaining one study from each OEM per quarter.

Introduction

Owing to the mechanical properties of Advanced High-Strength Steel (AHSS), the springback after forming and the geometric dimensional control of the stamped parts has been a critical issue in stamping tool construction and in stamping production. Because the actual dimensions of AHSS stampings off the tooling are unpredictable with current tools and technology, the average die face re-machining may be four to six times normal and result in two to three months of lost tryout time.

Computer simulation technology has been widely applied in the stamping industry and has been recognized as a virtual stamping tool to identify formability issues and evaluate solutions before the actual stamping dies are made. Although computer simulation provides an accurate prediction for splits and buckles, experience has shown that computer

simulation data has not been totally reliable in predicting the amounts and modes of the springback, twist or sidewall curl. These distortions must be controlled if the AHSS is to be used successfully for lightweight body structures. Innovative stamping processes that neutralize residual stresses resulting from the metal deformation may control springback and other distortions in high strength steel stampings. These processes will involve some type of stretch forming in order to give the stamping "shape set". The work of this project group is to determine the most effective means of researching and applying these "shape set" processes. Computer simulation is also being analyzed to improve the data input for accurate formability prediction.

Benchmarks Toward Meeting Deliverables

Fender Rail Die

To assess the accuracy of the current forming/springback control theories, a full-scale fender rail-stamping die was used (Figure 1). A lockstep was added to the die to provide sidewall stretch and the potential for splits. For this reason, the project team has solicited, received and evaluated proposals for work in the area of fracture analysis to support future formability analysis in dies.

Several different AHSS materials, including Dual Phase 600, 780 and 980 were used to stamp fender rails and the finished panels were measured by laser scan. Springback control experiments were conducted using tooling designed to replicate actual production stamping die processes. These experiments confirmed the importance of stretching the sidewalls during the stamping process in order to reduce residual stress, flange springback and part-to-part variation. However, DP600 MPa and lower strength materials were the only materials that could be stretched with a two-break lockstep. Higher strength material (DP780 MPa and DP 980 MPa) required a four-break lock step for effective stretch results (Figures 2 and 3).

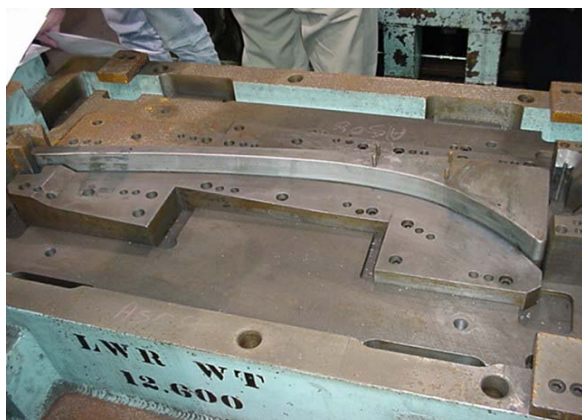


Figure 1. Fender Rail Die – Lower Half.

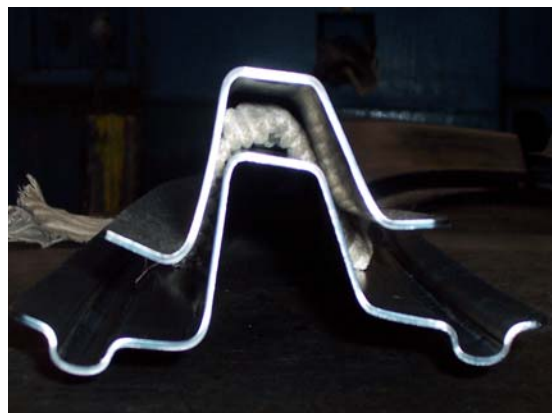


Figure 2. Effect of stretch with four-break lock step. Note that top section was not stretched.

Multi-Process Master Shoe Die

The Project Group is focused on experimenting with a multi-process research die with sub-die inserts (Figure 3) to produce various automotive structural components by a variety of processes. This die has the necessary higher holding pressures and controlled processes required for working the higher strength materials.

A programmable hydraulic pressure cushion is the main component of this system that provides the means of stretch forming the metal and controlling springback. Four sub-die inserts were built for this tool by the end of 2006.

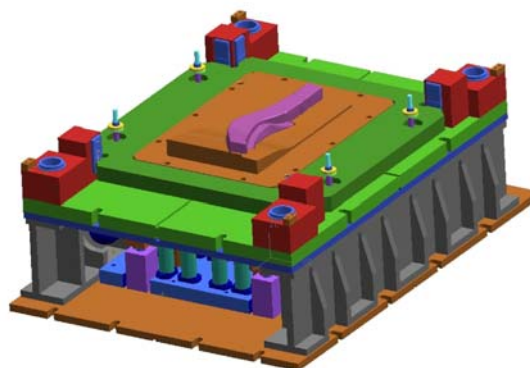


Figure 3. Lower Half of Multi-Process Die.

Sub-die inserts in the multi-process master shoe die enable stamping of underbody, cross-car and body side structural components with a variety of stamping processes.

Rear Longitudinal Rail Sub-Dies

Tryout of the three different stamping processes and with 1.6 mm and 2.2 mm DP600 MPa steel and 1.6 mm DP780 MPa and DP980 MPa steel have shown that the higher strength materials tend to split when drawn and are more readily formed than drawn. Press loads were monitored and lower press loads were noted when using the forming process. Material utilization was also much more efficient when using the forming process (Figure 4). Future efforts will feature continued work with the higher strength grades to improve the springback control with “shape set” features, such as lock steps, added to the forming process.



Figure 4. Rail Stampings Three Processes.

Cowl Cross Member Sub-Die

A Cowl Cross Member sub-die is part of the program. This stamping tryout also shows that the higher strength steels are more easily formed than drawn for some panel configurations (Figure 5). Additional stampings will be produced with DP600, 780 and 980 MPa materials using various blank configurations. These stampings have been laser scanned and the dimensional data has been recorded and analyzed to determine the effectiveness of each process.



Figure 5. Cowl Cross-Bar Two Processes.

Additional Work

Body Side Center Pillar Sub-Die

Another sub-die for a Body Center Pillar has been completed in December of 2005 (Figure 6).



Figure 6. Body Side Center Pillar.

This part is crucial to the body side structure for meeting side impact requirements. It is also typically difficult to stamp in medium strength grades due to springback, twist and undercrown. The higher strength grades will increase the manufacturing difficulties.

By recording the results of innovative forming processes, case studies for specific structural parts will be presented, along with product design and stamping process guidelines for industry reference, when making product applications of the AHSS materials.

In addition, stamping press tonnages are being recorded, along with, impact loads, press signature analysis and die cushion pressure requirements for the stamping industry's information. This will aid in better understanding the machine and equipment requirements for manufacturing components from this material.

Further stamping tryouts of DP600, DP780, and DP980 will be conducted on typical automotive underbody, cross-car and side structural members with new tooling and multiple processes. These materials, in lighter gauges than currently employed, will assist the weight reduction and structural performance goals of the Future Generation Passenger Compartment and other light weighting project groups in the Auto/Steel Partnership.

Conclusions

The dual phase steels of 600 MPa to 980 MPa can be formed more readily than drawn. Product should be designed to allow a form die process for structural parts in the higher strength grades.

Draw die processes and stretch-form processes will be required for large outer "skin" panels of 500 MPa and lower. Product design modifications may be required to use these materials instead of lower strength grades.

When AHSS is formed, a "shape set" stretch should be added at the bottom of the press stroke for springback compensation.

Stretch flanges are very susceptible to edge cracking and flange edge stretch may be minimized by product design. Trim edge quality will be critical.

Presentations and Publications

1. "Product and Process Effects on Stamping Performance of Advanced High Strength Steels." *Presented at the March 8, 2006 seminar "Great Designs in Steel" in Livonia, Michigan.*
2. "Product and Process Effects on Stamping Performance of Advanced High Strength Steels." *Presented at the September 19, 2006 International Auto Body Congress in Novi, Michigan.*

ⁱ Denotes project 050 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

U. Strain-Rate Characterization (ASP 190ⁱ)

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Contractor: United States Automotive Materials Partnership

Contract No.: DE-FC05-02OR22910

Objectives

- Develop new experimental setups for characterization of crashworthiness and strain-rate sensitivity of both high-strength steels (HSS) and structural designs.
- Replicate impact conditions that occur in automotive impact by simpler and more manageable experiments in order to generate meaningful data for computer modeling.

Accomplishments

- Developed experimental setup procedures for new crashworthiness characterization test based on parallel-plates buckling, a procedure developed at the University of Dayton Research Institute (UDRI).
- Developed and conducted constant-velocity crash experiments on circular tubes made of mild steel, dual-phase and transformation-induced plasticity steels.
- Developed graphics-oriented tools for data analysis from parallel-plate and tube-crush experiments

Future Direction

- Develop experiments for characterizing strain and strain-rate history in tubular components in octagonal, spot welded double-hat tube crush tests.
 - Provide high-quality data for material and finite-element modeling (FEM) development.
-

Introduction

Crashworthiness characterization of HSS requires testing of materials and structures under increased strain-rates, large plastic strains, and large displacements that are characteristic of actual impact events. Aside from providing a physically quantitative measure of crashworthiness, the experiments also provide benchmarks for verification of FEM models that are used for automotive design and analysis. Typical crashworthiness experiments involve crushing of tubular objects, such as circular or rectangular tubes. Due to a combination of relatively high velocities and force levels required for progressive crushing, the experiments are usually conducted in inertia-based equipment, such as drop towers or impact sleds. For example, in a drop tower the drop height and the drop mass can be adjusted to generate desired crush force and length. However, there are practical limits on the mass and the velocity that can be used in a drop tower. The kinetic energy of the impact must be such that it can be expended in the deformation of the specimen and the safety restraints in order not to damage the testing equipment. Vibrations of the falling mass are practically impossible to eliminate, and the lateral forces are not easily measured nor controlled. The velocity of impact cannot be kept constant and gradually reduces from the onset of impact.

The objective of this project is to develop and conduct coupon- and component-level experiments for the characterization of crashworthiness of HSS. The project will also provide high-quality data for development of material and structural FEM models, and, therefore, enable more accurate modeling and design of lightweight crashworthy vehicles.

Design of Experiments

Tube Crush Experiments

To improve experimental investigations of the material and structural behavior for automotive impact, the Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (ACC) of USCAR have developed a new integrated virtual and physical test system for hydraulic, high-force, high-velocity crashworthiness experiments of

automotive materials and structures. The unique system, a test machine for automotive crashworthiness (TMAC), permits controlled, progressive crush experiments at programmable velocity profiles and high force levels. More details about the TMAC system can be found on <http://www.ntrc.org>.

The tube crush experiments were conducted at the National Transportation Research Center user facility in Oak Ridge, Tennessee. The TMAC system is shown in Figure 1.



Figure 1. Test machine for automotive crashworthiness.

The ability to control displacement (velocity) and the large lateral stiffness of the machine allows for strain history measurements that are not practical in drop tower equipment. TMAC's high load capacity allows for controlled velocity history during the test. This can be seen from the displacement history in Figure 2. The figure shows the progression of the displacement of the loading plate during the 4 m/s crush test. The slope of the displacement denotes velocity, which was constant for the duration of the first 18 milliseconds corresponding to the investigated tube crush length.

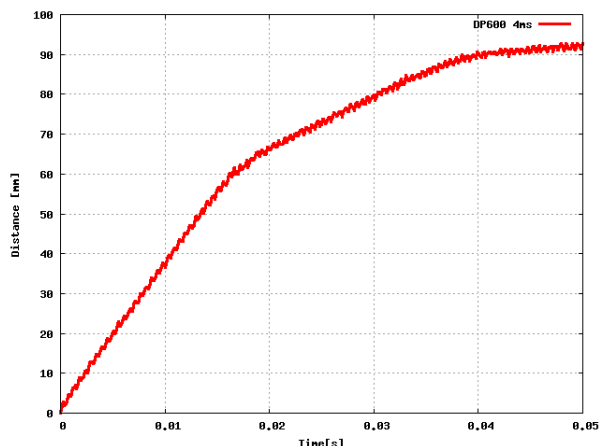


Figure 2. Displacement history for the 4 m/s tube crush.

At this, relatively high, velocity, the data-acquisition-system effects become more pronounced compared to the lower crush speeds. The effects are visible in the small oscillations in distance in Figure 2. These oscillations are of relatively constant amplitude and frequency. The oscillations are of less importance at the low speeds but at high impact speeds may render some calculations invalid. The accurate displacements measurements are needed for deriving instantaneous velocities and crush energy and its rates. One of the possible remedies is to filter the derived quantities. However, such an approach does not clearly link the physical phenomena to the filter interval and its respective parameters. A better approach is to filter the data at the origin so that the data acquisition artifacts do not propagate in the data processing.

When raw displacement is plotted against the measured force for the purpose of calculating the crush energy, the oscillations in the measured displacements become more apparent with the crush-speed increase. This phenomenon is illustrated in Figure 3 where it can be seen that the displacement-force curves become more distorted with increasing crush speeds.

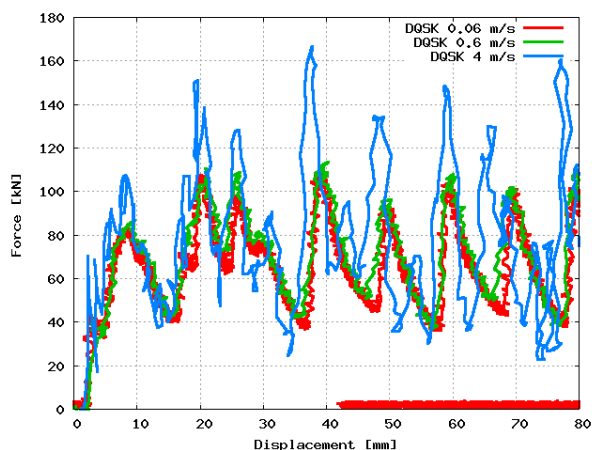


Figure 3. Displacement-force for the DQSK tube crush at various crush velocities.

It is natural to expect that the velocity-based quantities that are needed for rate-type measures will show even higher oscillations as the data-acquisition rate increases with the increasing crush velocity. When looking at the time-displacement trace for 4m/s impact in a short time interval, it was found that displacement raw data have a high-frequency oscillatory component. The displacement raw data were filtered using a second order Butterworth filter according to the SAE J211 with the cut-off frequency of 300Hz to yield a smooth velocity curve in accordance with observed optical traces from the high-speed camera and other system controls. The resulting displacement-force curves for the filtered displacement data are shown in Figure 4.

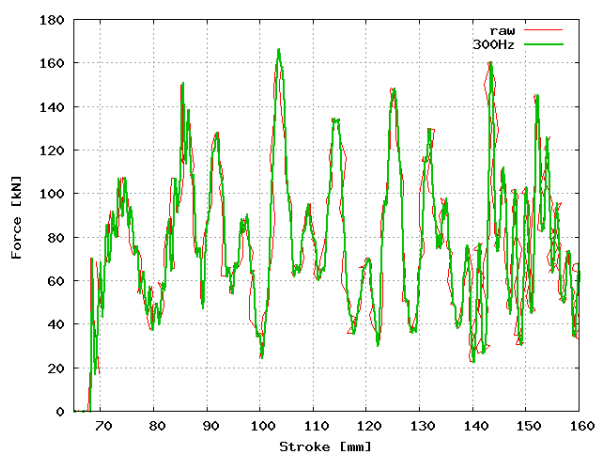


Figure 4. Displacement-force for the 4 m/s DQSK tube crush, entire test interval.

The data with processed displacements allow us to have better quality rate and energy measurements that are needed for characterization of crashworthiness efficiency and correlation with the FEM models.

The first set of materials tested in FY 2005 included mild steel (DQSK), high strength low alloy (HSLA) 350 MPa and dual phase (DP) 600 MPa steels. The test velocities were 0.06 m/s, 0.6 m/s and 4 m/s. These tests were completed in fiscal year (FY) 2006. Different test configurations were made to trigger symmetric and asymmetric crush modes. The symmetric mode is triggered in DQSK and HSLA350 tubes by a specially designed fixture. The DP600 tubes could not be symmetrically crushed primarily due to manufacturing imperfections that could not be overcome by the symmetric pre-crush. The asymmetric crush is triggered by the high imperfection at the impact end of the tube. Axially symmetric crush of HSLA350 tube is shown in Figure 5.

Asymmetric crush of DP600 tube is shown in Figure 6.

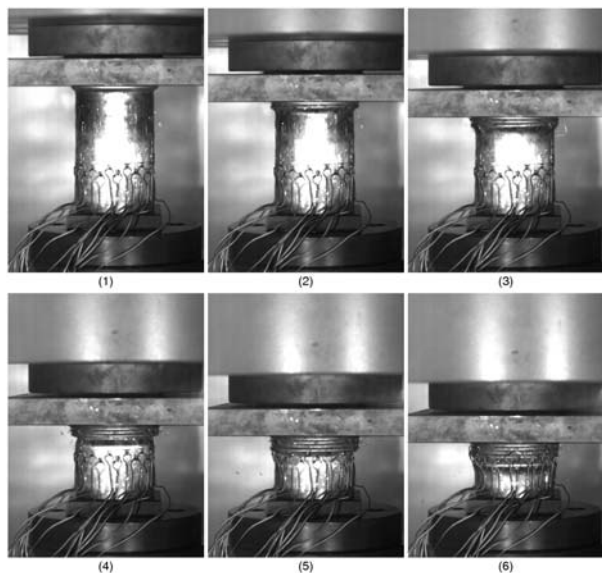


Figure 5. Progressive crush of a HSLA350 tube under constant velocity of 4 m/s. (Numbers below the photographs denote the relative time sequence).

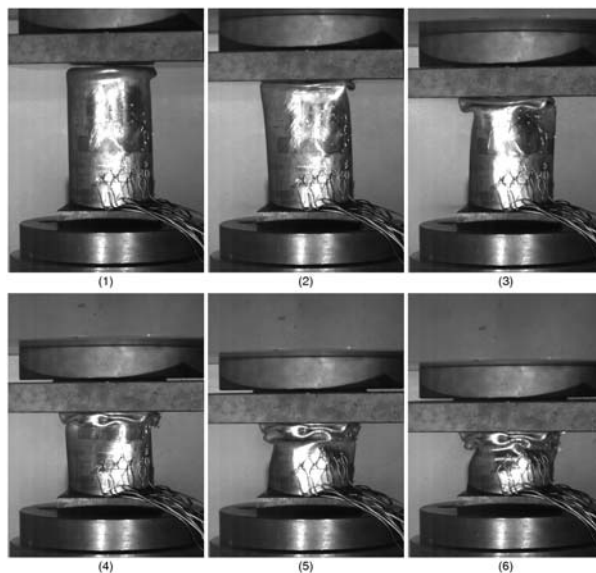


Figure 6. Progressive crush of a DP600 tube under constant velocity of 4 m/s. (Numbers below the photographs denote the relative time sequence).

The goal of the project is to measure and investigate the strain and strain-rate regimes that material experiences during the crush in order to improve predictive capabilities of the numerical models. The principal tools for strain-rate history measurement are electric resistance strain gages. The measured data for the first set of test materials is currently formatted and prepared for web-based data presentation.

A second set of advanced high-strength steel (AHSS) tubes are being tested. The materials included are transformation induced plasticity (TRIP), bake hardenable (BH), dual phase (DP), and interstitial free (IF) steels. The tests will be run under the same crush velocities. (0.06 m/s, 0.6 m/s and 4 m/s). The majority of materials were tested under 0.6 m/s and 4 m/s crush velocity. The remaining tests are scheduled to be completed during November of 2006.

Octagonal tubes made of spot welded profiles were manufactured and delivered for preliminary tests. The test specimen is shown in Figure 7.



Figure 7. Octagonal tube crush specimen.

The tests will be conducted using the same regime of crush velocities. The measurement of load variation with impact speeds and investigation of corner strains will be the focus of these tests. These tests will be conducted on eight different AISI material grades: BH300, 440W, DP800, TRIP590, TRIP780, TRIP980, Hot Rolled Dual Phase, and TRIP600. For each of these materials, nine tests will be run, corresponding to three replicates at three different test velocities. In each case, two out of the three replicates will be instrumented with a maximum of nine strain gages. The geometry of all the tubes will be the same for all material grades to allow for comparison and common tube fixturing.

Conclusions

Three steel materials have been tested under constant crush velocities. The constant crush velocity and hydraulic-based testing systems provide unique tightly-controlled testing environments for structural and material characterization. The experimental data are used for validation and evaluation of modeling approaches, and for development of modeling guidelines for HSS materials and structures under impact loads.

Acknowledgments

Support from the Auto/Steel Partnership Strain-rate Characterization Team is acknowledged.

Future Work

The future work on the project will focus on three topics:

1. Circular tube crush experiments in TMAC test machine for AHSS sheet materials (2nd set)
2. Crushing of octagonal tubes in TMAC test machine. The geometry is characteristic of the front-end designs of new prototype vehicles.
3. Development of new coupon- and structure-level crash characterization experiments.

ⁱ Denotes project 190 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

V. Modeling of High Strain-Rate Deformation of Steel Structures

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Contract No.: DE-AC05-00OR22725

Objectives

- The objective of the project is to develop numerical modeling guidelines in order to realistically assess the influence that the properties of strain-rate-dependent materials exert in crashworthiness computations. The dynamic-loading problems are modeled using diverse combinations of modeling approaches (sub-models) that are essential in describing strain-rate sensitivity in computational simulations. Efforts have been focused in a number of technical areas including finite element method (FEM) formulations, constitutive materials models, material properties under different strain-rates and loading conditions, contact conditions, etc., as well as material property changes caused by component processing.

Accomplishments

- Investigated effects of stress transients for high strength steels (HSSs) and their effects on peak impact force
- Developed experimental setup for new crashworthiness characterization test based on parallel-plates buckling
- Developed program for analysis of history of strain-rate calculations
- Analyzed history of strain-rates in unsymmetric crushing
- Determined modeling effects on strain-rate history in unsymmetric crushing
- Develop new constitutive models for HSS to account for strain-rate history and transients
- Investigated forming and welding effects on steel tube crashworthiness
- Developed model for tube roll-forming and validated it against manufacturing process
- Developed experimental guidelines based on the two parallel-plates and tube crush tests

Future Direction

- Conduct and analyze octagonal tube crush experiments replicating HSS front rail
- Determine optimal FEM formulations for modeling of crushing of tubes with corners

Introduction

The objective of the project is to develop numerical modeling guidelines for strain-rate-dependent materials in crashworthiness computations. The scope of the project is to study specific structural problems in automotive impact, develop new experimental and analytical techniques for characterization of strain-rate sensitivity of HSS and modeling of complex strain and strain-rate histories. The dynamic-loading problems are modeled using diverse combinations of modeling approaches (sub-models) that are essential in describing strain-rate sensitivity in computational simulations. Sub-models to be examined include finite element formulations, constitutive materials models, contact conditions, etc. The trends, influences, and direct effects of employed modeling techniques will be identified and documented. The relative significance of employed sub-models is established, particularly in relation to the strain-rate effect resulting from the material constitutive models.

The research project is conducted as a team effort between the ORNL and the Auto/Steel Partnership Strain-Rate Characterization Group (see 2.U). Recent results have been published at the International Auto body Conference IABC 2006 [1].

Simulation of Double Plate Experiment

A new experimental setup has been developed for investigation of progressive crush in HSS. The objective of the experiment is to replicate components of loading conditions that occur during progressive crush of tubular structures in a simple structure to minimize the complexity of the problem. The simplicity of the specimen allows for simple correlation with the FEM experiments and for characterization of strain-rate sensitivity effects in basic impact energy-absorption mechanism. The experiment has been used for investigation of inertia and strain-rate effects in Type II structures by Tam and Calladine [2]. Our version of experiment is conducted for three different constant crushing velocities in order to assess the effect of crushing

speeds and strain-rate in off-axis compression and bending. The effects of material model types, model parameters, finite element (FE) shell element formulations and spatial discretizations have been included in the study.

A typical test is shown in Figure 1. The specimen is made of two pre-bent parallel plates and is impacted from the bottom and crushed with constant velocity. Figure 1 shows the edge view of the specimen. The forming process has been simulated using the quasi-static material properties. The edge of the simulated plate is superimposed over the image from the experiment and shown as a dark line and marked as "Simulation". The impact loading was imposed using the displacement history of the loading plate from the experiment. Superimposed images of the simulations over the experimental results from the high-speed camera test are shown in Figure 1. The images are ordered in the time sequence.

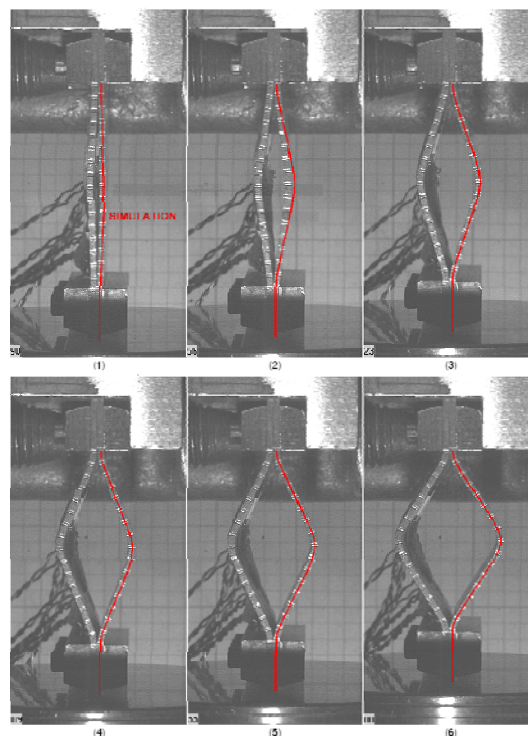


Figure 1. HSLA350 plate crush test. Crush velocity 0.6 m/s.

Simulation results exhibit more flexibility during early stage of impact compared to the experiments in all materials tested. During the early phase of impact, FEM models buckle faster than experiments. Experiment data later catch up with the simulations and the two are essentially overlapped during the rest of the test. Several reasons for the discrepancy are possible and are currently being investigated. The experiment was simulated using different modeling approaches. The comparison of force history between experiments with different impact velocities and simulations is shown in Figure 2. The simulations use a strain-rate-sensitivity model based on plastic strain-rate formulation.

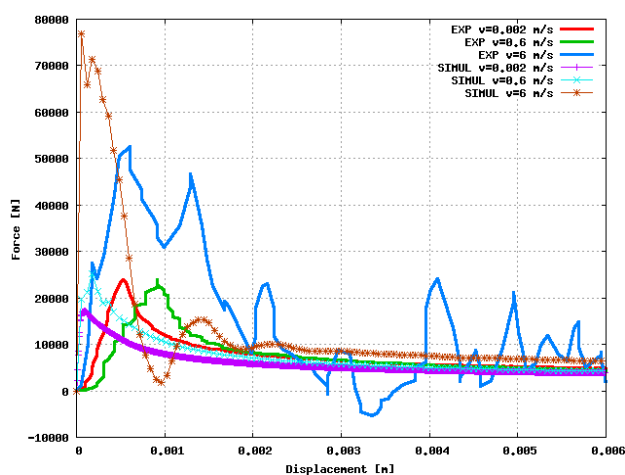


Figure 2. Double plate crush test forces. Experiment vs. simulations.

It was found that the model based on total strain-rate formulation does not lead to realistic strain-stress history in the elements experiencing severe plastic deformation in the plastic hinge areas. Due to the experiment configuration, this discrepancy is reflected on global level such as the force history. A comparison between different formulation results is illustrated in Figure 3.

Analysis of the elements in plastic zones shows that the total strain-rate formulations result in higher stresses and therefore a stiffer structural response compared to plastic strain-rate formulations. The effect is more apparent at intermediate impact speeds where the saturation strain-rate data are lower than the applied rate. In the case where the saturation rate is reached by both formulations, the

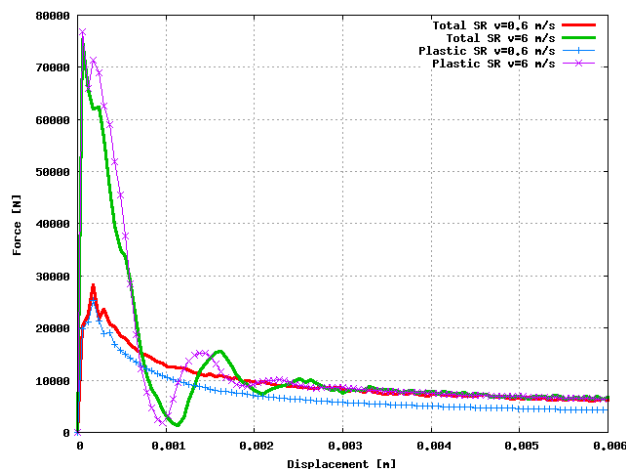


Figure 3. Double plate crush test forces. Total vs. plastic strain-rate formulations.

respective model responses are almost the same. A strain history data comparison for experiments and simulations based on total plastic strain-rate is shown in Figure 4.

The double-plate test has been used to develop modeling guidelines for basic folding mechanism in crash. It was shown that the element discretization required to accurately match the deforming geometry is on the order of material thickness and that the strain-rate-sensitivity effects should be based on plastic strain-rate formulations. Total strain-rate formulation results in stiffer response and the strain-stress history does not match the imposed loading conditions. From the experimental

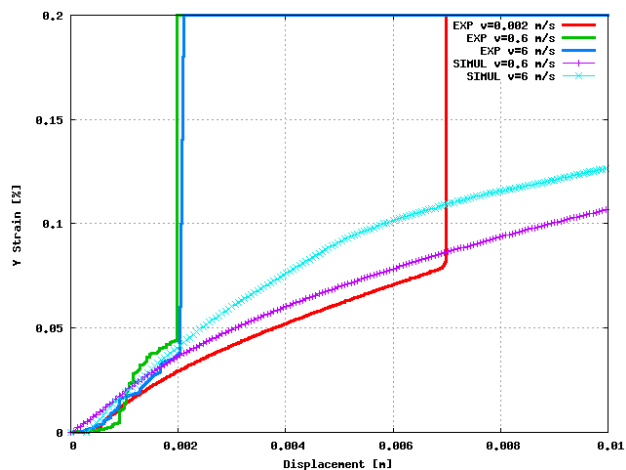


Figure 4. Comparison of test and simulation of strain histories for different impact velocities.

standpoint the main advantages of the double plate impact test are its similarity to principal energy dissipation mechanism in sheet steel under impact, relatively low force requirements, no gage section instability and capability of measuring large strains. The test will be further developed in order to provide a standardized method for measurement of crashworthiness of materials and strain-rate sensitivity in off-axis compression and bending.

Simulation of Axisymmetric Tube Crush

Tests

Structural component experiments have been developed using the new, velocity-controlled high-speed hydraulic Test Machine for Automotive Crashworthiness (TMAC) at ORNL.

Due to the axial symmetry of the problem, we can simplify the problem by analyzing a radial segment of the tube length with symmetry boundary conditions imposed in the hoop direction. The comparison between the measured and simulated impact force for high-strength low-alloy (HSLA) 350 tubes crushed at 0.6 m/s and 4 m/s crush are shown in Figures 5 and 6, respectively. Fully integrated elements with side length equal to two plate thicknesses were used.

The overall agreement between the model and the experiment is good. The agreement can be further improved by using finer resolution. However, in large structural simulations such an approach is still not practical. The results illustrate the need for new FEM shell element formulations that would be capable of modeling localized deformation with relatively coarse discretization.

Conclusion

New experiment configurations have been developed for characterization of crashworthiness of steel sheet materials. The experiments are based on hydraulic-based testing systems. The systems provide tightly controlled testing environments for material and structural characterization of basic mechanisms of impact-energy dissipation. The main advantages of the double-plate impact test are its similarity to principal energy dissipation mechanism

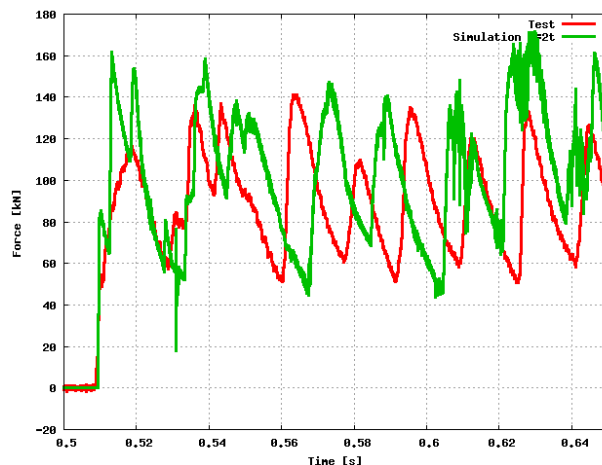


Figure 5. Comparison of test and simulation of 0.6 m/s tube crush, HSLA350.

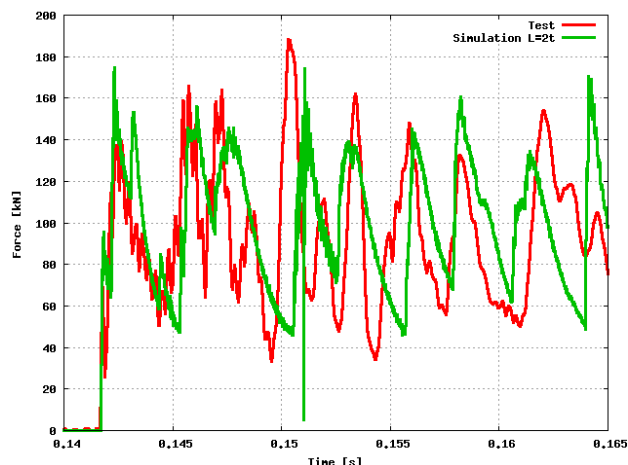


Figure 6. Comparison of test and simulation of 4 m/s tube crush, HSLA350.

in sheet steel under impact, relatively low force requirements, no gage section instability and capability of measuring large strains. The constant-velocity tube crush test enables characterization on component level and overcomes limitations of the inertia-driven equipment. The experimental data are used for development of modeling guidelines for steel sheet materials and structures under impact loads. Various FEM modeling approaches have been considered, such as material constitutive models, element formulation and discretization, and modeling of contact conditions.

Future Work

The future work on the project will focus on four topics:

1. Support of the strain-rate experiments on coupon and component level.
2. Development and validation of material models and modeling techniques.
3. Modeling of HSS octagonal tubes.
4. Development of models and experiments for damage and fracture of HSS in crash.

The remaining most important aspects to address from the modeling of HSS crashworthiness are the methods to model the crush of tubes with rectangular (polygonal) cross section.

Acknowledgments

The research was performed at the Oak Ridge National Laboratory (ORNL), which is managed by UT-Battelle, LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725. The tubes for the TMAC experiments were donated by the US Steel Corporation. The support of Auto/Steel Partnership Strain-rate Characterization Team (see 2.U) is acknowledged.

Contact

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W. Lightweight Front End Structures (ASP110ⁱ)

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Contract No.: DE-FC05-02OR22910

Objective

- The objective of the Auto/Steel Partnership (A/SP) Lightweight Front Structure (LWFS) project is to benchmark, develop and document solutions that balance the interaction of material, manufacturing and performance in the lightweighting of automotive structures. The initial phase of this study focused on automotive front-end system solutions that address high-volume manufacturing and assembly. Furthermore, example solutions were manufactured and physical testing was performed to evaluate the advanced high-strength steel (AHSS) designs.
- The AHSS solutions will provide choices and consequences that address real-world challenges faced in the vehicle development process. A comprehensive knowledge-base design tool was developed to capitalize on a set of robust AHSS automotive design guidelines relating choices to consequences.

Approach

- An existing front rail system from a donor vehicle was retrofitted with AHSS Dual Phase (DP) 800 steel to save 22% of the mass. In addition, a front bumper made from DP980 steel replaced the existing bumper design.

- The AHSS rail system and bumper were manufactured and tested to compare performance with the conventional design it replaced.
- Analytical and physical testing was carried out on both the original and the redesigned rail system.
- Comparisons will now be drawn and recommended practices documented.

Accomplishments: Additional Phase 2 Deliverables

- Selected a stamped-rail concept.
- Obtained final optimized stamped-rail and bumper designs.
- Completed formability simulation of the stamped design.
- Generated computer aided design (CAD) data for manufacturing of the new stamped-rail and bumper designs.
- Developed prototype tools for manufacturing rail and bumper stampings.
- Manufactured prototype dies for the rails, rail extensions and bumper.
- Developed new welding schedules for AHSS joining.
- Developed static and dynamic stiffness design of experiment (DoE) finite element (FE) models.
- Developed static-stiffness DoE response surface.
- Developed dynamic-stiffness DoE response surface.
- Stamped and assembled rails, rail components and bumpers.
- Prepared the donor vehicle to accommodate the new rails and bumper.
- Installed the new AHSS rails and bumper into the vehicle.
- Conducted a successful (certified) Insurance Institute for Highway Safety (IIHS) 35 mile-per-hour crash test of the retrofitted vehicle and recorded the results.
- Correlated the vehicle crash test data with the analytical results.
- Updated Proteus, a knowledge-base tool, with the findings of this project.
- Published a final report detailing all of the findings of this project, including lessons learned.
- Tech transfer of project results (Deep Dive Presentation) conducted at DaimlerChrysler.
- Project results “display” was completed and used in road-show presentations.
- The original Phase 1 and Phase 2 have been completed.

Future Direction

- Initiate a project to develop mass-efficient design solutions using AHSS to meet FMVSS-214, IIHS and global requirements of the front structure and chassis and provide bandwidth to enable OEM implementation.

Manufacturing Feasibility

The primary intent of the Lightweight Front End Structures project was to demonstrate the mass-savings potential of advanced high strength steel combined with efficient design in an existing production-vehicle package space while addressing manufacturing feasibility. To ensure manufacturing feasibility, several A/SP enabler teams were utilized to review the design recognizing that the members

of these teams represent the manufacturing interests of their companies and ensured that the project developed a solution that addressed manufacturing feasibility. The enabler teams were consulted to assist in developing designs and designs were modified to accommodate enabler-teams’ design review comments.

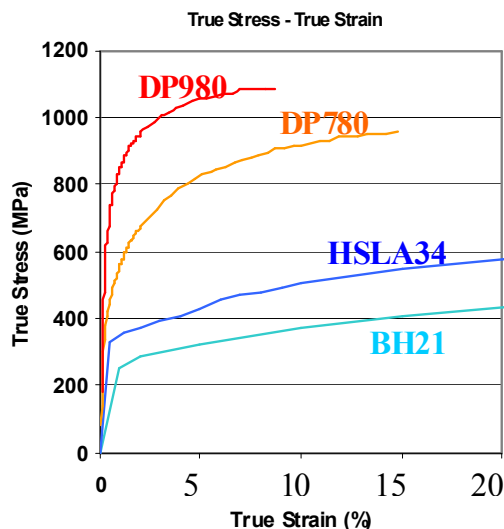


Figure 1. True Stress-True Strain Curves.

The Lightweight Front End Structures team would like to recognize the efforts of the A/SP High-Strength Steel Stamping (see 2.T) team, Hydroformed Materials and Lubricants (see 2.Q) team, Strain-Rate Characterization (see 2.U and 2.V) team and the High-Strength Steel Joining Technologies (see 2.P) team for their overview and support of the project.

The project team went to every effort, within the confines of the program, to demonstrate manufacturing feasibility. The project does not address manufacturing capability required to understand the influence of the many variables of a high-volume manufacturing environment. The extent to which manufacturing-feasibility is addressed is documented in the following sections.

The manufacturing feasibility report is composed of the input from many of the participants of the program. Detailed chapters are provided for each of the key manufacturing areas. The following is a summary of the manufacturing feasibility section of the report.

Materials

The redesigned rail bumper / system relies on DP780 and DP980 steels, grades that are commercially available from North American sheet-steel producers. The existing rail design utilizes steel in strength ranges from BH210 to HSLA340 compared to the new optimized design that utilizes

DP780 and DP980. The mass-saving potential of different steel grades in a crash event can best be compared by the relative area under the true-stress / true-strain curve between 0 and 10%, as shown in Figure 1.



Figure 2. Rail inner and rail outer laser-welded blanks.

It is the high ductility of these grades that enables the stamping of the components and application to the rail/bumper system. In comparison, a HSLA 800 grade has a total elongation of 3% to 4% compared to 16% to 19% for DP780. Prior to applying the AHSS grades to automotive applications, such limitation in ductility has prevented the stamping of steels at these strength levels into rail and bumper components.

Laser Welded Blanks

Six of the 12 stamping comprising the redesigned rail / bumper system are produced using laser-welded blanks (LWB) of DP780 and are a key design feature required for structural efficiency and affordability.

The LWB are primarily responsible for the part consolidation achieved in the redesign, reducing the part count from 27 parts in the original design to 13 on the redesigned system. The blanks were manufactured under production conditions, with no special edge preparations in the blanking operations and the equipment run at production speed.

Laser-weld seam quality was evaluated for geometrical imperfections and tested with an Olsen tester. The testing indicated the blanks met all quality requirements. The weld seam produced by the laser-welding process was usually convex, displayed a narrow weld seam and a very small heat-

affected zone. Examples of microstructures for DP780 Hot Dip Galvanized (HDG) steel after laser welding are shown in Figure 3. Micro-hardness values indicate that the welds are typical of a good quality laser welding process and demonstrate high feasibility for industrial applications of DP780 LWB.

The most severe testing placed on the laser-welded blanks was during both the actual stamping operations and in the crash event where the laser welds performed as expected and without incident.

Stamping

Steel stamping dies were built to produce the prototype components, with the exception of the rail extension, which used a soft tool for the draw operation. The process is designed to produce components representative of a production operation. The process is also intended to investigate and address manufacturing feasibility within the confines of the project. The detailed report describes each component as in the following example of the rail extension, which was the most difficult stamping.

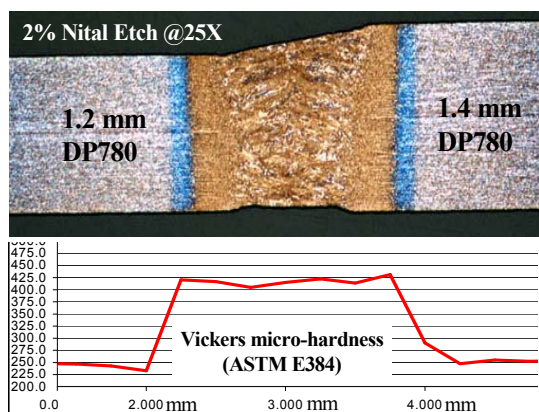


Figure 3. Laser welds HAZ and micro-hardness.

A prototyping process was developed to produce the part, in this case a five-stage operation.

Finite-element analysis (FEA) simulation was used to address the feasibility of forming the component. In this case, failure was predicted but it was felt a solution could be developed during die development.

Blank optimization was utilized to allow the steel to draw into the die and address potential splitting and wrinkling concerns.

A single-piece draw die was used to form the part. As predicted by the forming simulation, the parts did demonstrate forming problems. Several design changes were required to address splitting issues, including opening the sidewalls and changing the binder pad surface to improve material flow.

Are-strike tool was required to finish-form the sidewall and correct the sidewall springback.

Finally, a checking fixture was used to confirm conformance to design and understand and address springback issues. A graphic representation of the above is shown in Figure 4.

It was anticipated that trimming was to be accomplished by laser or saw operations in prototyping. However, the parts configuration accommodates a typical trim die operation.

A recommended production process is accomplished for each component. This is a conservative approach and the intent would be to look for design concessions and process improvements to reduce the number of operations.

Tooling reports

Tooling reports were performed on each of the stampings to understand final part severity and the need for additional work on each part. The tooling report for the rail extensions is shown in Figure 5. The analysis shows that several locations on the parts are not safe and additional die modifications or part concessions are required for a production-ready stamping.

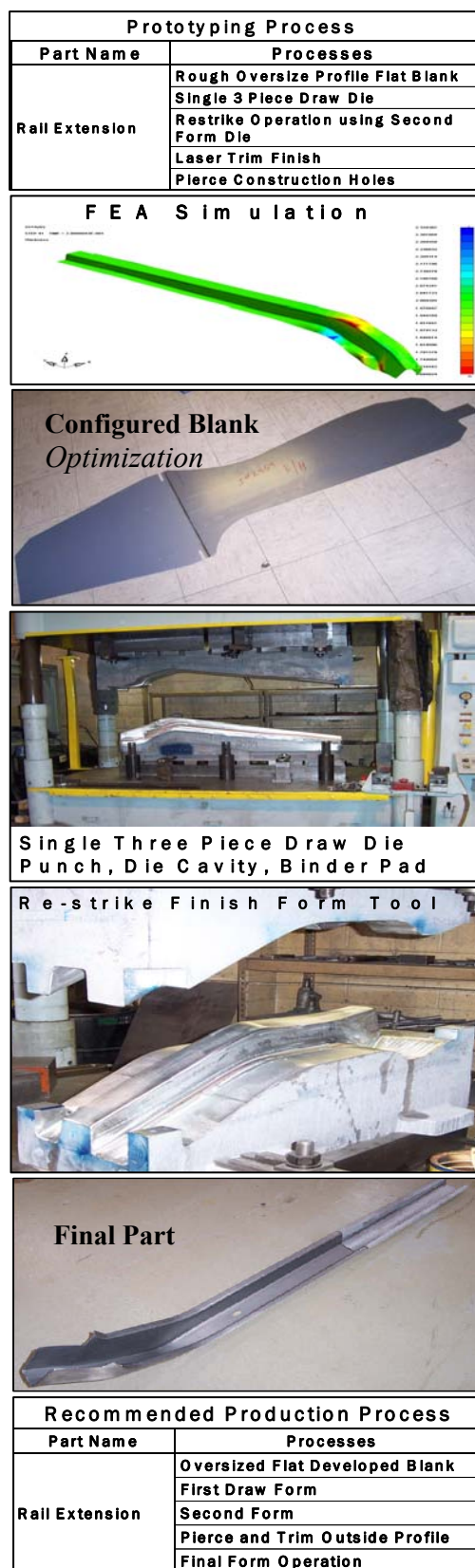


Figure 4. Stamping process flow diagram.

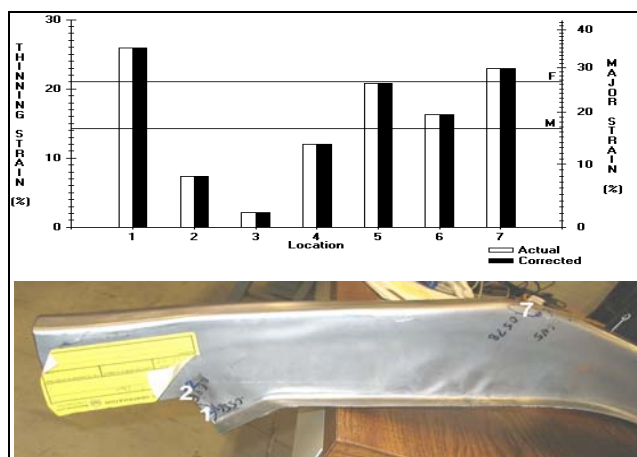


Figure 5. Rail extension tooling report.

The forming-strain evaluations shown in figure 6 indicate that, in addition to the rail extension, the rail-extension reinforcement and the bumper stampings do not meet a safe criterion. The dies have been assigned to the A/SP HSS Stamping Team (see 2.T) for additional development and the improved understanding required for production of these steel grades.

Part	Grade & Gauge & Coating	YS (MPa)	TS (MPa)	%El	n-value (terminal)	Part Forming Status	
						Status	Safety Margin
Rail Inner (3 pc. LWB)	DP780 1.0mm GA	489	875	16.6	0.116	Safe	18.50%
	DP780 1.2mm GA	508	896	16.4	0.113	Safe	10.80%
	DP780 1.4mm GA	429	837	19.2	0.118	Safe	12.90%
Rail Outer (3 pc. LWB)	DP780 1.0mm GA	489	875	16.6	0.116	Safe	18.50%
	DP780 1.2mm GA	508	896	16.4	0.113	Safe	13.30%
	DP780 1.4mm GA	429	837	19.2	0.118	Safe	13.50%
Rail Inner Reinf.	DP780 2.0mm GA	495	892	13.6	0.111	Safe	16.70%
Rail Extension (2 pc. LWB)	DP780 1.2mm GA	508	896	16.4	0.113	Safe	11.90%
	DP780 2.0mm CR	517	806	23.0	0.111	Critical	-8.30%
Rail Ext. Reinf.	DP780 1.4mm GA	429	837	19.2	0.118	Marginal	6.10%
Bumper Inner	DP980 1.0mm CR	814	983	14.0	0.084	Marginal	1.20%
Bumper Outer	DP980 1.0mm CR	814	983	14.0	0.084	Critical	-3.80%

Figure 6. Tooling report summary table.

Spot Welding

The A/SP High-Strength Steel Joining (see 2.P) team developed weld schedules for the stack-ups required by the design as shown in Figure 7 on the following page. All resistance welds were produced using standard portable gun-style welders. The weld guns are typical of a body shop that uses manual welding.

Where single-side access was the only access to weld joints, material was drilled out on the top sheet to provide effective MIG puddle welds. This technique was used where the donor body was

Weld Schedules Specified For Materials In LWFS RAIL Assembly.

Stack up ID	Material Location	AISI	Metal Grade, Gage	Weld Cycles	Min/Max Current (kA)	Nominal Current kA (1)
114	TOP	-	DP980-1.03 mm			
	BOTTOM	-	DP890 1.03 mm	22	8.8-11.6	10.5
115	TOP	-	GA DP800 1.0 mm	22	8.8-12.4	11(2)
	BOTTOM	-	GA DP800 1.0 mm			
116	TOP		GA DP800 1.20 mm	22	9.0-10.8	10
	BOTTOM	208	GA DP800 1.20 mm			
117	TOP	209	GA DP800 1.40 mm	22	9.0-10.4	10.5(2)
	BOTTOM	209	GA DP800 1.40 mm			
118	TOP	210	HDG DP800 2.0 mm	22	10.0-11.5	10.8
	BOTTOM	209	GA DP800 1.40 mm			
119	TOP	208	GA DP800 1.20 mm	22	10.0-12.0	11.0(2)
	BOTTOM	210	HDG DP800 2.00 mm			
120	TOP	209	GA DP800 1.40 mm	22	10.0-11.5	10.8
	BOTTOM	210	HDG DP800 2.00 mm			
121	TOP	209	GA DP800 1.40 mm	22	9.8-11.0	10.8(2)
	MID	210	HDG DP800 2.00 mm			
	BOTTOM	209	GA DP800 1.40 mm			

Nominal force 1500 lbs, nominal hold 30 cycles, tips 45-degree truncated with 7.0 mm face.

GA = Galvanneal

HDG = hot dip galvanized

NOTES:

(1) Nominal current produced better than 97% good welds without weld tip stabilization.

(2) Required tip stabilization to obtain buttons on tip (point) evaluation test.

Figure 7. Weld schedules for specified materials.

attached to the rail assembly. This was a restriction of the prototype vehicle build and not indicative of what would be accomplished in a production assembly.

A post-crash inspection of the welds was undertaken to assess performance of the welds in the crash event. Observation of all visually-accessible rail welds indicated that no welds separated without

pulling buttons from adjacent material. The welds performed as expected in the crash event.

The study suggests that conventional equipment and processing would be able to deliver acceptable welds for these material combinations.

Assembly

The assembly was a “one-off” build and is the least representative aspect of a production process and little was gained toward the demonstration of manufacturing feasibility. An assembly fixture, shown in Figure 8, was used for the assembly of the rail and then for attachment to and alignment on the donor vehicle.



Figure 8. Modified rail assembly on check fixture.

It was noted that the parts fit together without the need for excessive clamping, indicating that the parts were near desired shape.

The project does not comprehend all of the manufacturing variables prevalent in a high-volume-manufacturing environment. However, this project does address several aspects of meeting those goals and can be used in the accumulation of knowledge

needed to develop robust manufacturing practices suitable for AHSS.

Testing

The AHSS rail and bumper designs were validated by conducting a New Car Assessment Program (NCAP) 35-miles-per-hour rigid-barrier impact test at the Transportation Research Center in East Liberty, Ohio. The bumper and the front section of the rails crushed completely and there was no significant deformation of the A-Pillar, B-Pillar, roof rails and rail extension rear. The B-pillar acceleration peak of the new AHSS design was lower than that of the baseline design; however,

the time-to-stop of the new AHSS design was longer than that of the baseline design.

There are two observations to be noted relating to the condition of the test vehicle:

- it had been driven prior to this test, and
- the engine and engine mounts from a previously-crashed vehicle were used.

Overall, the new AHSS design had an NCAP performance similar to that of the baseline design.

Photos 1 through 7 provide visual and graphic representation of pre- and post-test conditions.



Photo 1. NCAP test – LH side views.



Photo 2. NCAP test - front views.

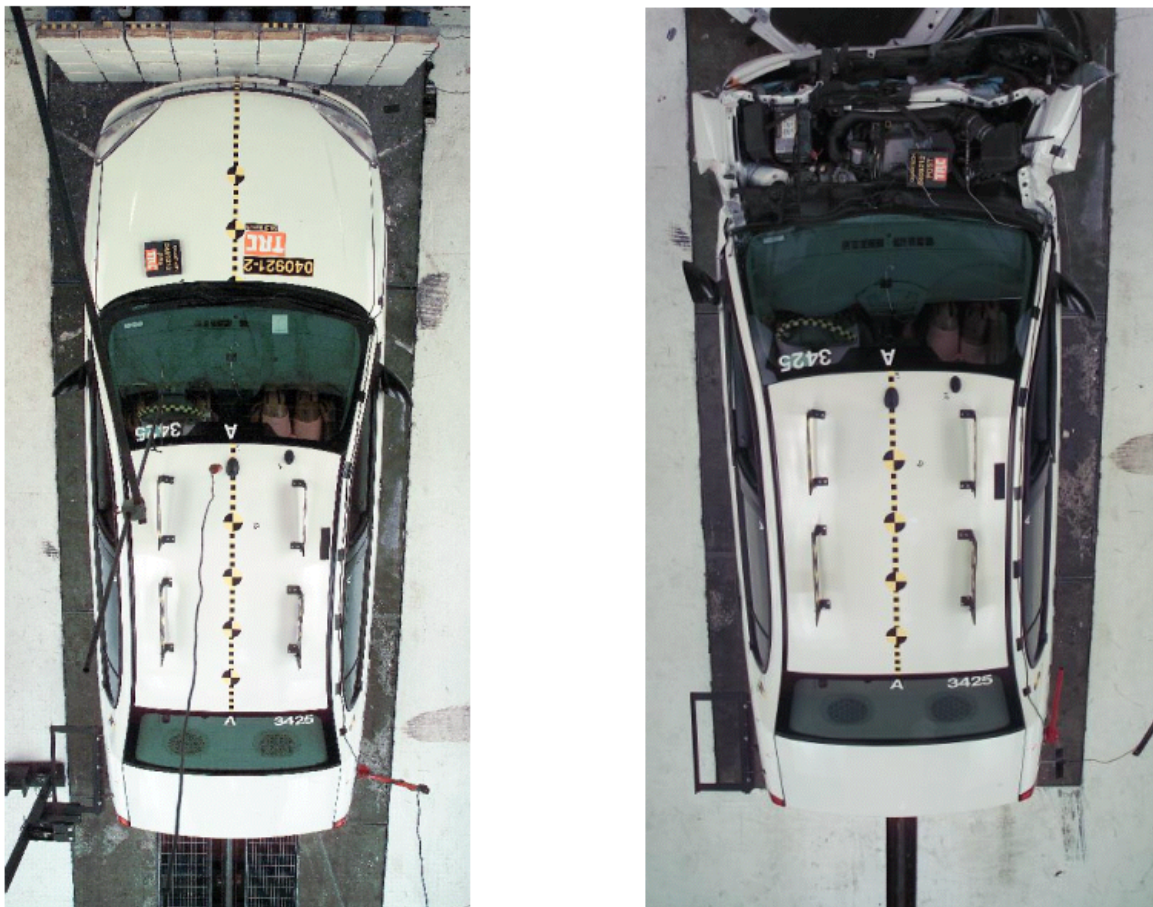


Photo 3. NCAP test - top views.

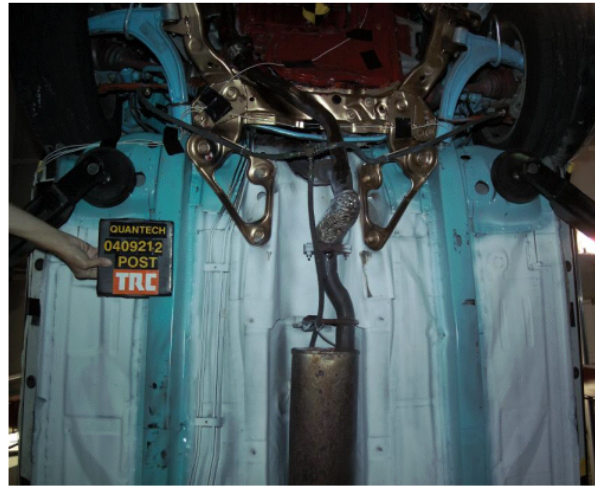
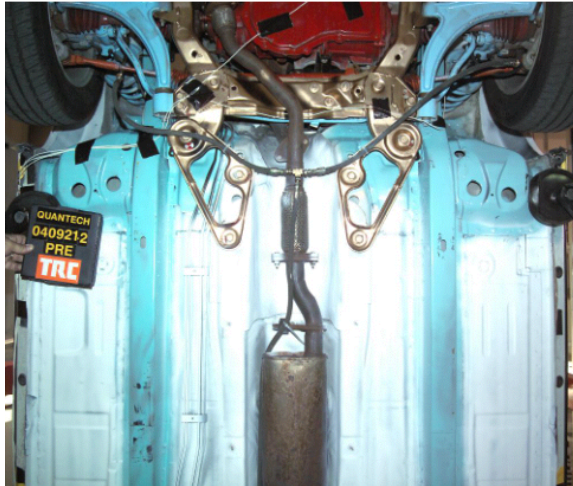


Photo 4. NCAP test - underbody views.



Photo 5. NCAP test – front end/bumper view.



RH



LH

Photo 6. NCAP test - bumper close-up views.



RH



LH

Photo 7. NCAP test - front rail views.

Figures 9 & 10 compare B-Pillar deceleration pulse between baseline donor vehicle and the Lightweight Front End Structure test results.

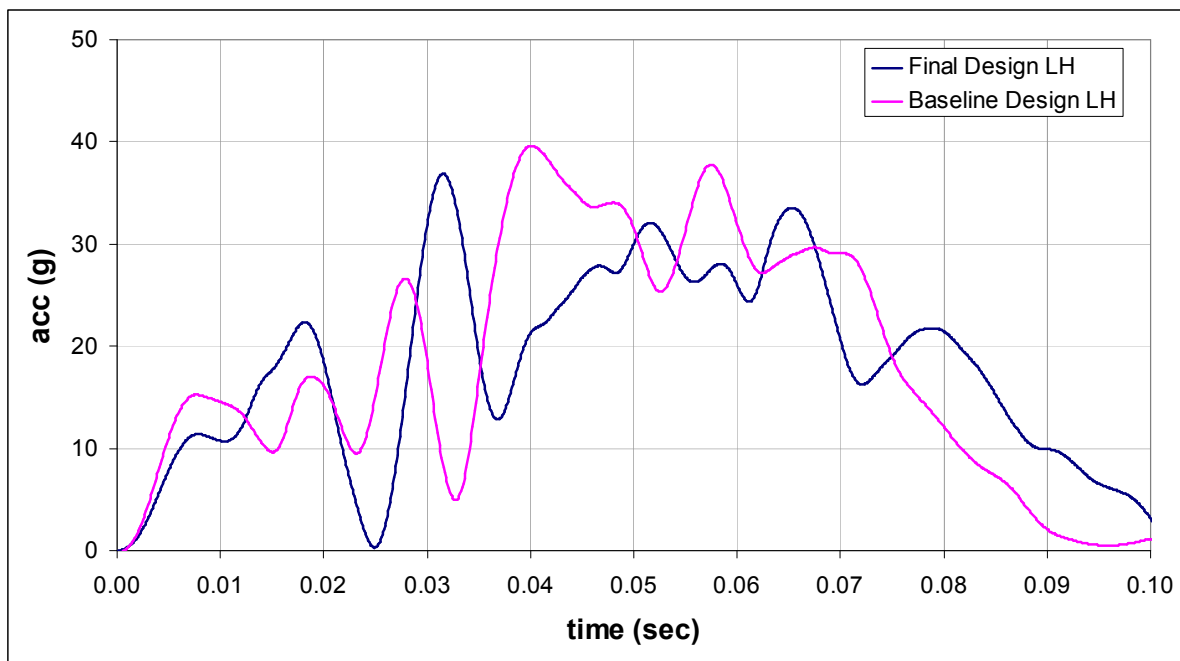


Figure 9. NCAP test – left hand b-pillar acceleration pulse comparison.

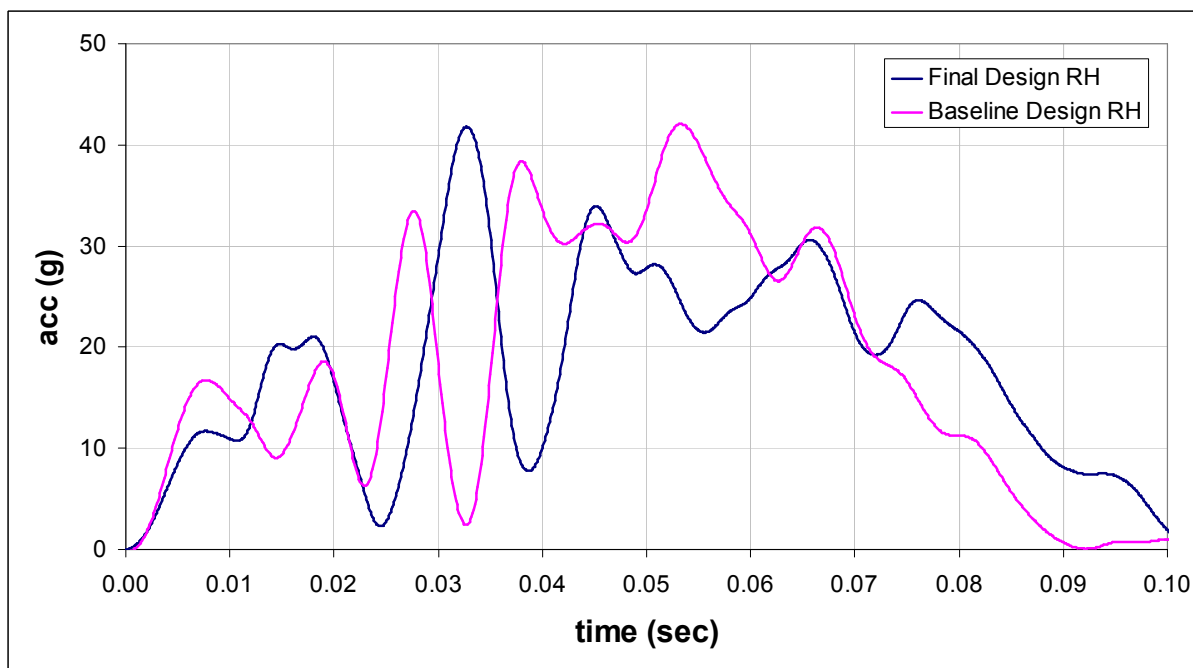


Figure 10. NCAP test – right hand b-pillar acceleration pulse comparison.

Post Crash Report of Weld Performance

The crash test was performed with all front structure components in-place, including engine, suspension and heating and air-conditioning equipment. The original-design structural components are painted white. All structural adhesive and sealers were applied per the production requirements of the original design. The AHSS components that were redesigned to replace the original steel rails are painted blue. The apron assembly, or shock tower, was not part of the redesigned LWFS rail project.

The body structure was mounted on a 45-degree viewing rack to allow easy access to areas of interest. Due to the mounting, the most easily photographed rail components were on the RH side of the body.

Where single-side access was the only access to weld joints, material was drilled out on the top sheet to provide effective metal inert gas (MIG) puddle welds. This technique was used where the donor body was attached to the rail assembly. One joint on the rail assembly restricted access of the weld gun and plug welds were used in place of resistance spot-welds (RSW) for some welds in

this joint. The bumper-reinforcement attachment bracket was also arc welded to the end of the rail assembly. All resistance welds were produced using standard portable gun-style welders. The weld guns are typical of a body shop that employs manual welding. All arc welding was performed using standard body shop MIG welding equipment and E70 filler wire. Observation of the post-crash weld conditions suggests that conventional equipment and processing should be able to deliver acceptable welds for these material combinations.

Observation of all visually-accessible rail welds did not indicate that any welds separated without pulling buttons from adjacent material. Photos 8 through 17 show principal views of the rails and associated assemblies. The performance of the welded rail assembly is largely un-remarkable as welds performed as intended.

Weld pitch was approximately 37 mm for the heavier stock. The closest pitch for RSW was approximately 25 mm.

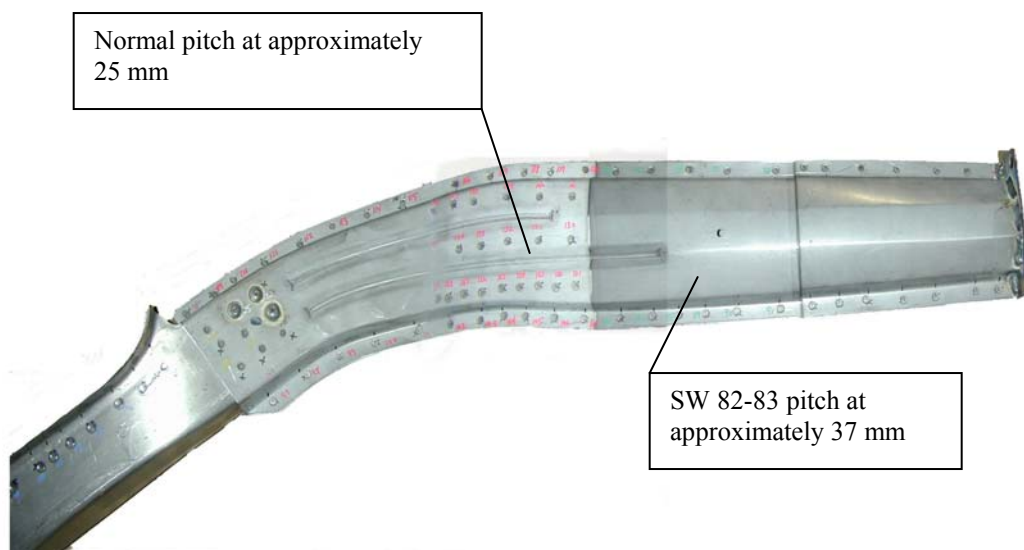


Photo 8. A portion of the right-hand rail assembly showing spot pattern layout prior to crash testing. This view does not include the rail length extending under the floor pan of the body.



Photo 9. Pitch for spot welds from bumper attachment to end of tailor-welded blank.



Photo 10. Standard MIG puddle welds were used where RSW guns would not fit into the box section.

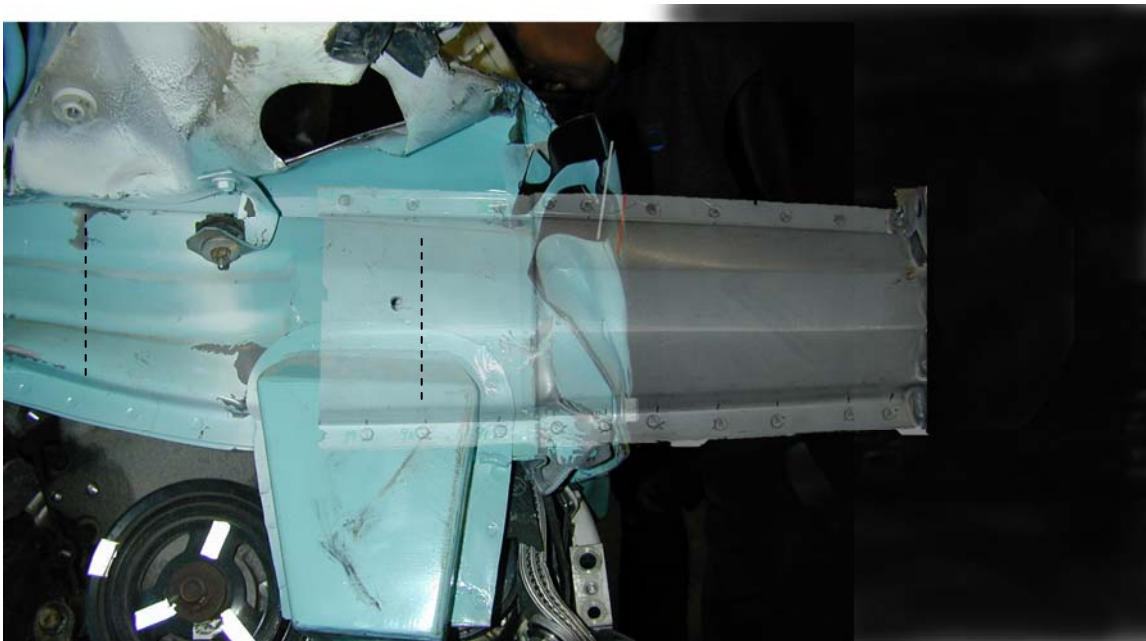


Photo 11. View showing right hand rail assembly with phantom view of original rail superimposed. The lighter gray shows AHSS crash materials. Dashed lines are approximate location of the laser welded blank joints.

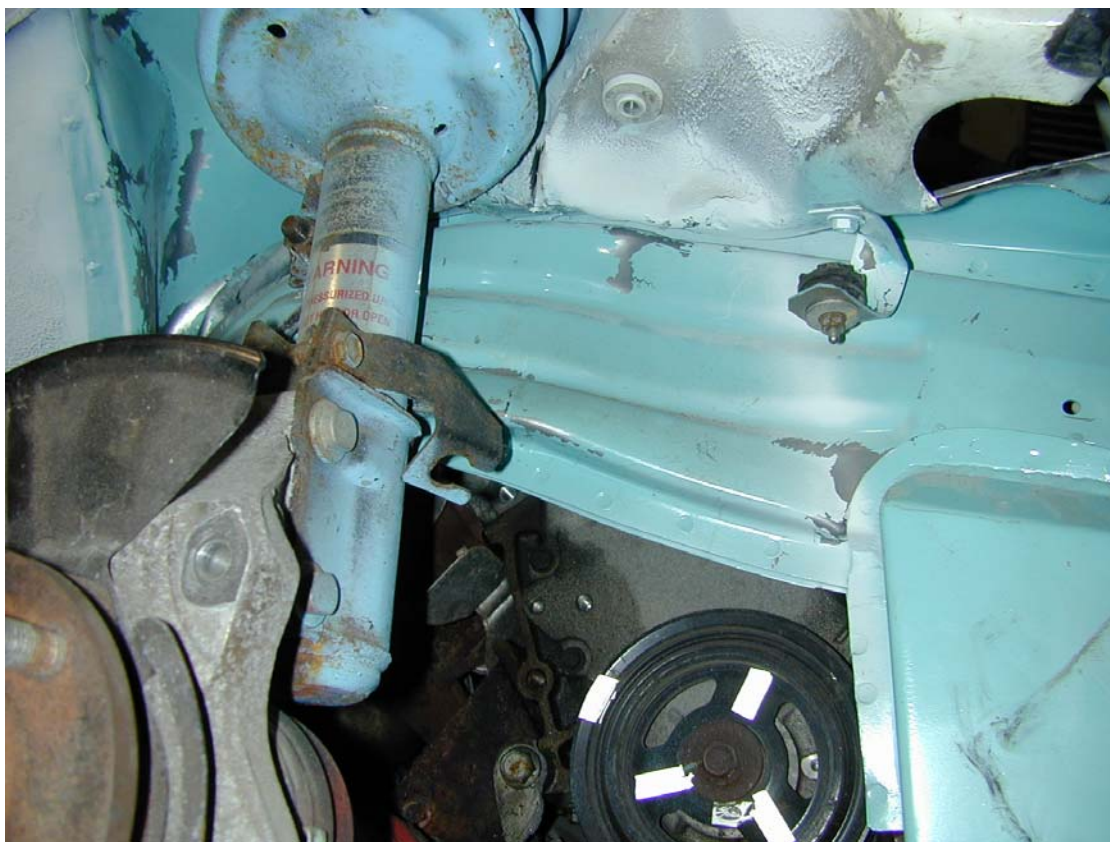


Photo 12. Right-hand rail aft of laser welded blank joints.



Photo 13. Slip joint with resistance spot and MIG puddle welds highlighted.



Photo 14. Left-hand rail to bumper reinforcement collapse. Weld buttons were pulled from the AHSS materials when separation was observed.

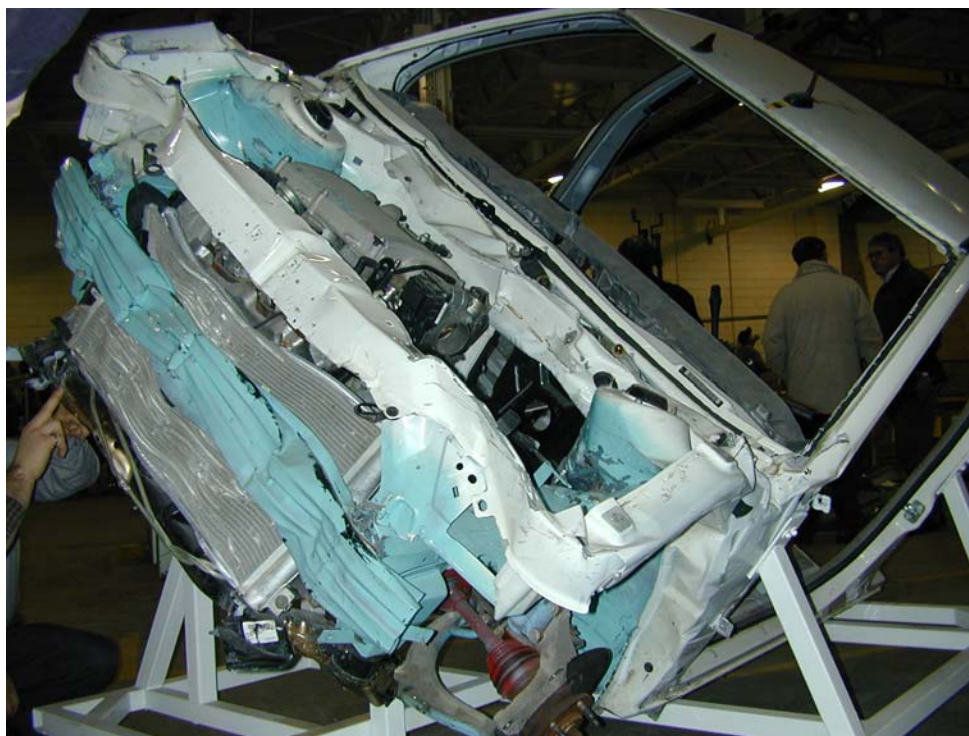


Photo 15. Front view showing bumper reinforcement and rail collapse. All welds were acceptable.



Photo 16. Left-hand side view of test vehicle.

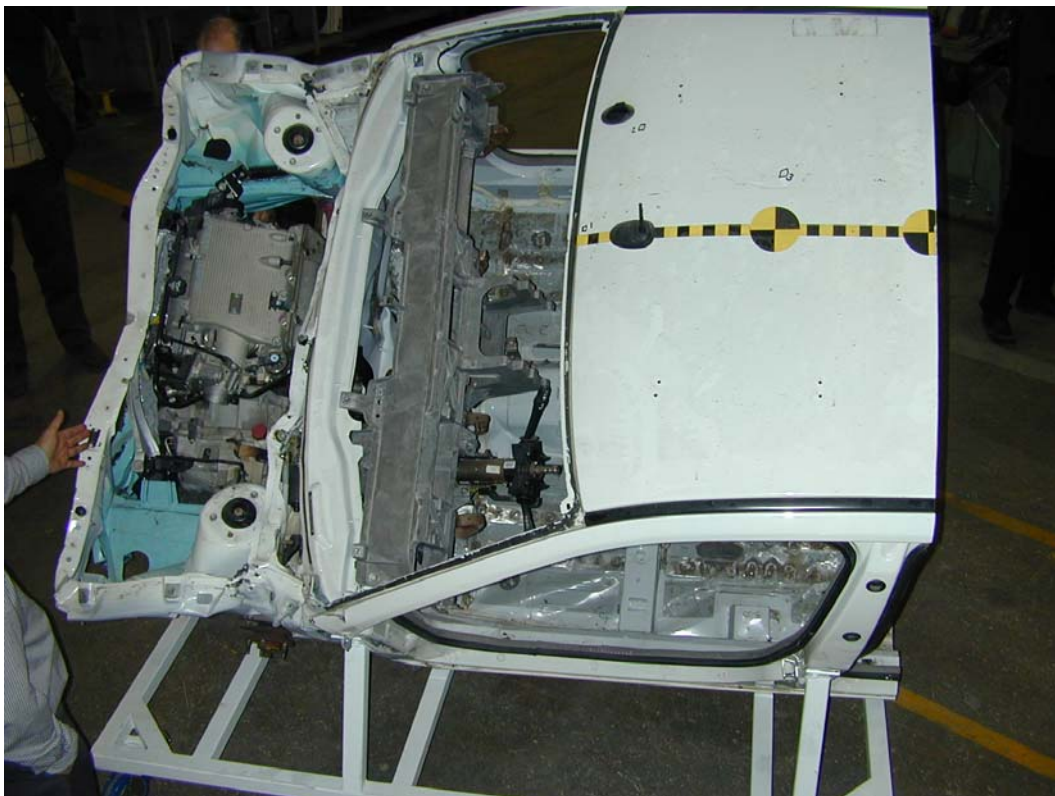


Photo 17. Body - top view. Note power train components contacting radiator support and dash panel.

Conclusion

The front rails and bumper were designed and fabricated using AHSS DP800 and DP980. The AHSS Design achieved a mass reduction of 8.77 kg (22.36%) compared to the baseline design. The performance of the AHSS design was similar to that of the baseline design. Conducting an NCAP 35 mph rigid barrier impact test on the donor vehicle fitted with the AHSS rails and bumper validated the AHSS design.

It can be concluded that the use of AHSS in conjunction with effective part design can result in significant mass reductions without compromising crash performance. Priority should be given to design stability and load path as opposed to maximizing sections. Parts can be manufactured using DP800 and DP980 steels, provided proper attention is given to manufacturing constraints early in the design process.

Technology Transfer

Final results from Phase 1 and Phase 2 were rolled out at “Great Designs in Steel” (GDIS) seminar held in March 2005, including the completion of the display and backdrop with the crash vehicle front-end and project results.

Subsequently a deep dive presentation was given to DaimlerChrysler engineers by the project team and a workshop conducted. A front end for a future DCX vehicle was selected to allow a comparison by the A/SP project team representatives against the project results.

Further deep-dive type presentations were conducted at General Motors and Ford Motor Company as a means to allow their product engineers to compare future vehicles with these results in a similar manner.

The engineering Phase 1 & Phase 2 final reports with project results have been completed and on the Auto/Steel Partnership website at www.a-sp.org, as well as media and public opportunities.

Since an enhancement to the hydroform rail solution was completed, it can be found in ASP060 semi-annual report along with the LWFES cost model results.

ⁱ Denotes project 110 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

X. Future Generation Passenger Compartment (ASP240ⁱ)

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Contractor: U.S. Automotive Materials Partnership (USAMP)

Contract No.: DE-FC05-02OR22910

Project Background

- Various studies conducted by the automotive OEMs (original equipment manufacturers), American Iron & Steel Institute (AISI), International Iron & Steel Institute (IISI) and the Auto/Steel Partnership (A/SP) have clearly demonstrated that AHSS (advanced high strength steel) can be effectively utilized in automotive lightweighting, or mass-avoidance strategies, to provide the required performance at a lower overall cost. New methodologies and designs must be developed to achieve equal or improved functionally and performance when compared to traditional design, while simultaneously ensuring cost-effective manufacturability of the appropriate automotive systems.
- Choices pertaining to design, manufacturing and materials are closely related. However, a thorough understanding and documentation of such choices and consequences does not exist today. Addressing this issue, along with bridging other technological “gaps”, is a prerequisite for enabling the use of steel in lightweighting automotive structures. Recent technologies anticipate multifunctional and multidisciplinary systems that can use the current and future AHSS in combination with an innovative optimized design.
- The USAMP and A/SP strategy for the FGPC project is to propose a new safety cage and underbody that can provide the OEMs with an example of AHSS usage in combination with a highly optimized design.

Phase 1- Objective

- The objective of the Future Generation Passenger Compartment (FGPC) project is to incorporate current propulsion systems and fuel cell-technologies into concept architectures. This project will reduce passenger compartment mass by 25% or greater with cost parity relative to FreedomCAR baseline while meeting the structural crash performance objectives for the IIHS side impact test and anticipated future crash requirements for the FMVSS pole side impact test and FMVSS 2.5x vehicle weight roof strength test. Further, it will maintain performance in static and dynamic stiffness, durability and front and rear crash requirements and also comprehend packaging requirements for fuel-cell powertrains. The study will address a 5-passenger 4-door sedan donor vehicle design and finally identify opportunities for steel properties that exceed the capability of existing automotive steel grades to improve light weighting potential.

Phase 1-Approach: Concept Development

The project will take a clean-sheet approach to developing mass-efficient structural load paths and select the most appropriate use of existing and future high strength-steels which include Dual Phase, Transformation Induced Plasticity (TRIP), Complex Phase (CP), Hot-Stamped Boron, Martensite, and New Application of Nano Obstacles (NANO) and definitions of future grades using targeted material properties.

The study will benchmark, develop and document integrated solutions that will balance the interaction of materials, manufacturing, performance and cost. In addition, it will focus on solutions that will address high-volume manufacturing and assembly applied to fuel-cell technology vehicles. The project supports the goals of FreedomCAR as follows:

- High-strength steels are a mass-efficient solution in crash-dominated vehicle structures (e.g., body, closures, chassis, etc.) at a significant cost advantage versus other materials.
- A passenger compartment is thus an enabler to facilitate the application of other lightweight alloys to achieve half the vehicle mass while maintaining affordability.
- Steel has the proven and existing infrastructure for high-volume production and 100% recycling.
- This and other projects also allow the industry to migrate to lightweight structures that will accommodate fuel-cell powertrains.

Phase 1-Accomplishments

- Passenger compartment mass was reduced by 31.4% relative to typical 2005 baseline vehicle at cost parity.
- Crash performance of donor vehicle was improved to achieve an IIHS side impact good rating, and meet FMVSS pole test and FMVSS roof strength requirements. IIHS side impact and pole test criteria were met, while roof strength performance was 3.3x vehicle weight exceeding the 2.5x requirement.
- Maintained performance in static and dynamic stiffness, durability and front and rear crash criteria.
- Packaging comprehended fuel-cell powertrain requirements. Identified that worst case loading scenarios for IIHS side impact was ICE (internal combustion engine) variant and not the fuel cell variant.
- Identified that steel grades with a tensile strength of 1600 MPa capable of meeting application manufacturing requirements (formability) could improve mass saving by 6 to 8 percent.
- Identified a load path at side-impact bumper height that carries crash loading across B-pillars is a significant load path to enable mass reduction.
- Solutions developed were verified to be robust to IIHS side impact bumper height variations and to vehicle weight increases.

Future Direction

- Validation of the Phase 1 results into a donated production vehicle design.
- Roll-out learnings into advanced vehicle development.
- Incorporate results into future production vehicles.

Introduction

The Future Generation Passenger Compartment (FGPC) project was divided into eleven (11) tasks.

- 1.0 Benchmarking
- 2.0 Calibration Baseline
- 2.5 Mass Redistribution
- 3.0 Optimization
- 4.0 Concept Design
- 5.0 Concept Design Analysis Check
- 5.5 Concept Design Check Supplement
- 6.0 Final Optimization
- 7.0 Final Optimization Design Check
- 7.5 Barrier Height & Curb Weight Sensitivity
- 8.0 Final Concept Design

1.0 Project Strategy

Develop a robust design that considered two different perspectives, near-term or 5-years and long-term or 15 years. Near-term is defined as the knowledge gained from FGPC Phase 1 used in combination with knowledge that could be applied to a present vehicle with minor modifications. Issues relating to manufacturing, joining and material selection are considered within reach. FGPC-Validation (Phase 2) will apply the knowledge gained in Phase 1 to a donor vehicle.

Near-term selection was driven by grade/gauge availability and by manufacturing capability. Although these considerations did include an appropriate amount of stretch, it is difficult to apply the specifics of these enabling technology requirements on a design concept.

The long-term perspective considers issues such as manufacturing components from materials that are not presently available or in gauges that current design practice would not view as practical. Hence, the steel industry will require further research to meet these challenges.

The long-term outlook also revised the underbody design to package both traditional diesel and fuel-cell powertrains. The diesel option was a conventional front-wheel-drive configuration. The second option considered packaging a fuel-cell and its fuel tanks. Design guidelines were developed for the major components of a fuel-cell vehicle, including hydrogen-storage tanks, batteries, fuel cell-stack, and electric drive, to meet established crashworthiness performance criteria.

Using the ULSAB-AVC BIW (body-in-white) as a base model, the FGPC objective was to model the BIW to accommodate both diesel and fuel-cell powertrains and to reduce the BIW mass while still meeting the requirements of the new IIHS side impact and roof crush regulations.

Strategy

1. Efficient use of geometry to define the load path that meets crashworthiness and stiffness requirements, while absorbing energy through total system topology optimization.
2. Investigate the usage of AHSS materials and manufacturing techniques, such as tailor-welded blanks, to reduce vehicle mass and increase its performance.
3. Reduce the vehicle mass by using topology and shape optimization.

1.0 Relative Material Costs:

In order to discourage the use of high-strength steel parts where it is not required, a cost penalty function was setup to estimate the relative cost of different associated with each grade selection. The cost factors defined in Table 1 were used to calculate the relative cost of each design. The cost of each part was calculated by multiplying the mass of the part with the normalized cost factor for the material considered.

Table 1. Relative material costs.

Material Name	Relative Cost
IF 140/270	1.0
DQSK 210/340	1.104
BH 250/550	1.13
DP 300/500	1.169
HSLA 350/600	1.1948
DP 350/600	1.39
DP 500/800	1.506
Boron 1550	1.805
DP 700/1000	1.584
Mart 1300	1.688

2.0 Structure & Material Independency

The strategy implemented by this project concentrated primarily upon multi-disciplinary load path optimization, which addressed all crashworthiness, stiffness and NVH loadcases under consideration. Once the most efficient load paths were defined, the second optimization was then allowed to review the gauge and material gauge of each individual component. Thus, when considering another material such as composite, aluminum or multi-material vehicle, the knowledge and technology developed by the load-path optimization in this project is still valid. However, the project has demonstrated, that the geometry, gauge, and the impact of manufacturing, joining, and assembly must be considered for each material proposed.

3.0 FGPC & Fuel Cell Opportunities

As part of the long-term perspective, the vehicle underbody was redesigned to be capable of accommodating both diesel and fuel cell powertrains. Task 2 evaluated the IIHS side-impact performance of both. Although both did not satisfy IIHS impact target, the fuel cell did provide improved performance over diesel. This was because fuel-cell components provided structural load paths during the crash that improved its performance. Consequently, the remainder of the design optimization focused on the diesel powertrain as the worst-case scenario, with the confidence that the final optimized design could be easily adapted to provide equivalent performance for the fuel cell.

4.0 Conclusions

The optimization methods applied to this study achieved an 11% mass reduction of the modified

parts of the BIW (body-in-white) and door impact beams (see Table 2) and 30% mass savings over a conventional, in-class vehicle's BIW and IP (instrument panel) beam (Table 3). Table 4 is a comparison of an industry-standard vehicle's safety cage to FGPC which shows a 31% mass reduction.

Table 2. Final mass summary for FGPC project-modified parts only.

Modified Parts	Baseline FGPC kg	Final FGPC kg	Mass Savings kg	Change %
BIW	130.6	121.0	9.6	7
Doors	12.6	6.4	6.2	49
Total	143.2	127.4	15.8	11

Table 3. Final mass summary for FGPC project-comparison to industry standard.

Structure	Industry Standard kg.	Final FGPC kg.	Mass Savings kg	Change %
BIW+IP Beam	310.0	217.6	92.4	30

Table 4. Final mass summary for FGPC project- safety cage comparison to industry standard.

Structure	Industry Standard kg	Final-FGPC kg	Mass Savings kg	Change %
Safety Cage	246.8	169.3	77.5	31

List of Presentations and Publications:

None at this time.

ⁱ Denotes project 240 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

Y. Lightweight Rear Chassis Structure (ASP601ⁱ)

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Contractor: U.S. Automotive Materials

Contract No.: DE-FC05-02OR22910

Objective

- Obtain a minimum mass reduction of 25% for a baseline passenger car rear chassis structure with no more than a 9% cost premium.
- Develop and document integrated solutions that balance the interaction of materials, manufacturing and cost. The solutions will focus on high volume manufacturing (200,000 plus vehicles per year).
- Develop a matrix of cause and effect for all variable parameters (+/- x kg in mass and +/- y dollars in cost for a given performance).
- Demonstrate the successful use of AHSS in a passenger car rear chassis structure.
- Address corrosion and durability issues associated with reduced thickness AHSS.

Approach

- Phase 1: Material optimization. Through material substitution and minimal size and shape changes, the goal is to reduce mass by 10%. Prototypes will be fabricated and tested. Completion is scheduled for January of 2007.
- Phase 2: Design optimization. Through a clean sheet redesign and the use of lessons learned in Phase 1, the goal is to obtain a minimum mass reduction of 25% with no more than a 9% cost premium. Prototypes will be fabricated and tested. Completion is scheduled for September of 2007.

- Phase 3: Communications. The goal is to transfer the technology developed in the project to OEM and Tier 1 chassis structure designers. Completion is scheduled for March of 2008.

Accomplishments

- Completed a Benchmark Study for passenger car and light truck chassis structures.
- Selected DaimlerChrysler's LX rear cradle as the donor chassis.
- Identified four technology gaps that prevent the use of AHSS in chassis structures.
- Designed the Phase 1 (Material Optimization) prototypes.
- Obtained uncoated DP590 and TRIP780 for the Phase 1 prototypes.
- Fabricated successfully five Phase 1 prototypes.
- Developed three unique concepts for the Phase 2 (Design Optimization) prototypes.
- Selected a hybrid concept for the Phase 2 prototypes.
- Prepared a preliminary design for the hybrid Phase 2 prototypes.
- Implemented a formal approach to technology gap analysis.

Future Direction

- Conduct physical testing on the Phase 1 prototypes.
- Complete the technology gap analysis and summarize the lessons learned.
- Undertake a cost study for the Phase 2 Preliminary Design.
- Finalize the Phase 2 Preliminary Design.
- Fabricate and test Phase 2 prototypes.
- Prepare Final Report for the project.
- Transfer the technology through road shows to A/SP member companies and key Tier 1 suppliers.

Project Progress

October 1/06 – September 30/06

1.0 Timeline

The original project timeline is shown in Table 1. The plan was to incorporate the lessons learned from Phase 1 into Phase 2. However, in September of 2006 it became clear it was impossible for this to happen. The Phase 1 prototypes had yet to be built let alone tested. Further, the Phase 2 design was nearing completion with little input from Phase 1. Thus, the Team decided to revise the timeline to that shown in Table 1. In essence, the timing for Phase 2 was pushed out to allow lessons learned from Phase 1 to be incorporated into the Phase 2 clean sheet design.

2.0 Phase 0: Baseline Structure (6/05 -7/05)

The rear chassis selected for this project is based on DaimlerChrysler's LX rear chassis (Figure 1).

DaimlerChrysler provided the CAD and FE models, specifications and design targets. In addition, DaimlerChrysler will conduct durability, NVH, impact and corrosion testing on the Phase 1 and 2 prototypes.

Table 1. Project Timeline.

	Original Timing	Revised Timing
Phase I		
a) Design	Jun/05- Jan/06	Jun/05- Aug/06
b) Gap Analysis	Jun/05- Jan/06	Jun/05- Jan/07
c) Prototype Build	Feb/06- Apr/06	Feb/06- Oct/06
d) Performance Testing	May/06- Jun/06	Oct/06- Dec/06
Phase II		
a) Design	Nov/05- Jul/06	Nov/05- Mar/07
b) Prototype Build	Aug/06- Sep/06	Apr/07- Jun/07
c) Performance Testing	Oct/06- Dec/06	July/07- Sep/07
Phase III		
a) Communications	Jan/07- Mar/07	Feb/07- Mar/08

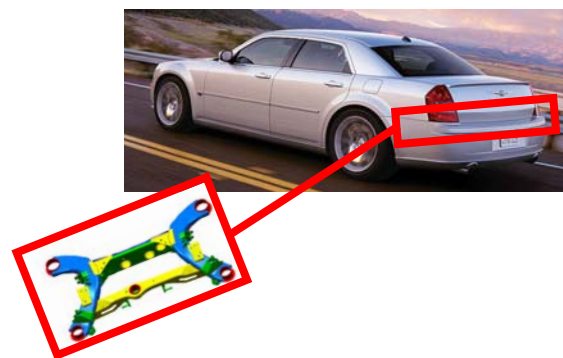


Figure 1. DaimlerChrysler LX rear chassis structure.

The actual rear chassis structure chosen as the baseline is a derivative of the LX rear chassis structure. Altair Engineering, as an in-kind contribution, prepared CAD and FE models for the baseline. The baseline structure is shown in Figure 2.

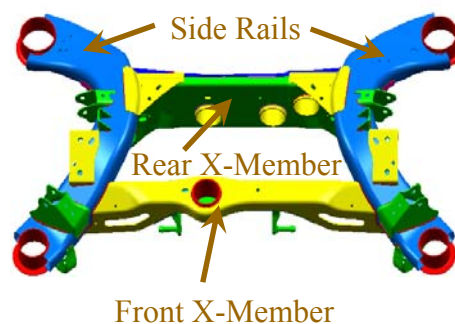


Figure 2a. Baseline structure.

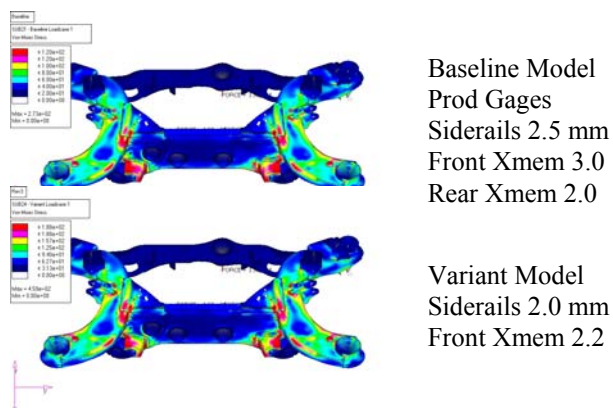


Figure 2b. Altair Phase 1 redesign.

3.0 Phase 1: Material Optimization

3.1 Phase 1a): Design Analysis (8/05 – 8/06)

Altair Engineering was retained by A/SP to reduce the baseline mass by 10% through material substitution and minimal size and shape changes. Altair, through trial and error, arrived at redesign steel grades and thicknesses as shown in Figure 3.

LX Rear Cradle	Base-line	Re-design
Side Rails	3.13mm 240 MPa	2.0mm DP590
Rear X-member	2.0mm 208 MPa	1.7mm DP590
Front X-member	3.7mm 362 MPa	2.2mm DP780
Weight (Est.)	29.14 kg	21.5 kg

Figure 3. Altair Phase 1a) Stresses for suspension load case number one.

Stresses, modes and stiffnesses were checked for four load cases: three suspensions and one torsion. For example, the stress check results for suspension load case number one are shown in Figure 3. As shown in Figure 2, the redesign mass was 21.5 kg, a mass reduction of 7.6 kg or 26%. This portion of the Phase 1a) work was conducted between 8/05 and 10/05. Altair's CAD and FE models were delivered to DaimlerChrysler.

Between October of 2005 and December of 2005, Altair conducted an "A" versus "B" fatigue comparison for the siderail. Although the stress in the siderail increased from 34 to 74 MPa, the fatigue life of the base steel increased by 20% because of the switch from low-carbon to DP590 steel. The fatigue strength of the MIG welds in the rear chassis structure is not sensitive to steel grade.

In December of 2005, Altair submitted the following conclusions for Phase 1a):

- Gage can be significantly decreased in most structural members using AHSS, and still meet stress targets.
- Stress at the weld joints increased significantly. The welded area should be redesigned to reduce stress in the weld.
- Fatigue life of the material does not increase proportional to the yield strength of the material, so fatigue of the structure should be analyzed.
- Normal modes of the structure reduce by approximately 10%.
- Dynamic stiffness of the structure decreases by approximately 10%.
- Miscellaneous brackets could be a significant source of weight reduction.

In March of 2006, The Team decided to make two design changes to Altair's Phase 1a) redesign. First, the front crossmember was changed from a two-piece closed section to a single-piece open section. Second the number of attachment points on the rear cross member was changed from three to two. DaimlerChrysler agreed to incorporate these changes into Altair's Phase 1a) CAD and FE models as an in-kind contribution to the project. DaimlerChrysler provided preliminary CAD data in June to the prototype supplier (Experi-Metal) and final CAD data in July. The CAD models did not include

welds. However, DaimlerChrysler provided weld sizes and lengths to Experi-Metal in August of 2006. DaimlerChrysler is adding the welds to the CAD model of the Phase 1 prototypes.

3.2 Phase 1b): Manufacturing Analysis (10/05 – 2/06)

The A/SP Rear Chassis Team, in consultation with A/SP forming experts, concluded there should be no difficulty in forming the DP590 rear crossmember and the DP780 front crossmember. However, the Team had strong reservations about the ability to hydroform the siderails from 2.0 mm DP590. Cosma and ThyssenKrupp Budd both agreed to undertake a forming analysis on the siderail as an in-kind contribution to the project. The Cosma and ThyssenKrupp hydroforming processes differ. Thus, the Team asked each company to undertake a forming analysis. Cosma's analysis concluded that during pre-bending, all of the DP590's ductility would be used up at the critical locations. Therefore, during hydroforming, splits would occur at these locations. ThyssenKrupp Budd arrived at a similar conclusion. In view of this finding, the Team decided to manufacture each siderail as a seamless clamshell.

As another in-kind contribution, Cosma delivered a presentation to the Team titled Hydroforming 101. An example slide is shown in Figure 4.

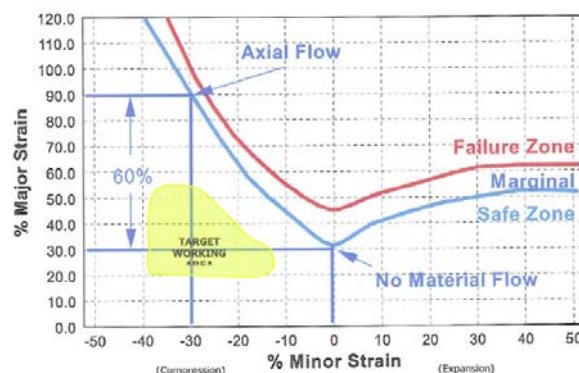


Figure 4. Advantages of material flow when hydroforming.

3.3 Phase 1c): Prototype Material and Build (12/05 – 10/06)

Starting in December of 2005, considerable effort was expended in locating material for the Phase 1 prototypes. Advanced High Strength Steels (AHSS) are in various stages of introduction to the marketplace. Many AHSS grades, especially uncoated and in the thicknesses associated with chassis structures, are not produced in North America. Thus, in addition to all North American steel mills in A/SP, leading steel mills in both Europe and Japan were contacted regarding availability. Another complicating factor was the need to have the prototype steel delivered by March 31, 2006 to satisfy our original prototype construction schedule. Arrangements were finalized in early March with Nippon Steel and Mittal Steel and the prototype material was received on schedule. Nippon and Mittal supplied the steel as in-kind. A comparison between the redesign material requirements and the actual steel obtained is shown in Table 2.

Table 2. Phase 1 Prototype Material

PHASE 1 REDESIGN	PHASE 1 ACTUAL
<u>NIPPON STEEL (Japan)</u>	
Front Xmember CR	
2.2mm DP780	2.3mm TRIP780
<u>MITTAL STEEL (USA)</u>	
Rear Xmember CR	
1.7mm DP 590	1.8mm DP590
Siderails CR	
2.0mm DP590	1.99mm DP590

The Team believes successful parts for the clamshell siderails can be fabricated from either DP780 or TRIP 780. Thus, because DP780 was unavailable, the Team selected TRIP 780, which was available. The thicknesses, again for the reason of availability, vary insignificantly from the redesign thicknesses.

The DP590 and TRIP780 prototype materials were subjected to physical and chemical tests.

The tests confirmed that the AHSS prototype materials met the requirements of SAE J2745 (February, 2006 draft).

Cosma fabricates the current LX rear chassis. Thus, in March of 2006, A/SP purchased from Cosma 10 sets of the carry-over parts required for the Phase 1 prototypes.

In January of 2006, an RFQ to build the Phase 1 prototypes was sent to five companies. Three companies submitted quotes. The Team placed two of them on a short list (Experi-Metal and Urgent Design and Manufacturing). These two companies were asked to a meeting to review their quotes. As a result of the discussions, the two firms were asked to re-quote. In February, the Team selected Experi-Metal to fabricate ten Phase 1 prototypes at a cost of \$135,150. Experi-Metal was given the redesign CAD and FE data, which Altair prepared between August and October of 2005.

As explained in Section 3.1, design changes meant that Experi-Metal did not receive preliminary CAD data until June and final CAD data until July. Thus, it became impossible to meet the original delivery date for the prototypes. On receipt of the preliminary CAD data in June, Experi-Metal commenced casting of the Kirksite zinc alloy dies for the AHSS stampings. In July, on receipt of the final CAD data, the dies were CNC cut. In August, on receipt of welding instructions, Experi-Metal built the first prototype. The mass (20.86kg) was below target. However, there were significant measurement deviations. In September, Experi-Metal built two more prototypes (Figure 5).



Figure 5. Phase 1 Prototype.

The dimensionality and weld quality in Build Number 3 was satisfactory and the Team authorized Experi-Metal to build five additional prototypes (in conformance with Build Number 3) for testing. The test prototypes are scheduled for delivery in October of 2006.

The Team plans to build the remaining two prototypes after the five prototypes have been tested. If required, one or two more prototypes will be built for additional testing. If not required for additional testing, one new prototype might be built with all 350 MPa HSLA steel to determine if the dimensionality issues are caused by the AHSS stampings. Also, if the large weld gaps in the five test prototypes cause issues during testing, one new prototype with all gaps <1.5mm might be constructed.

The prototype build phase of the project should be completed by January of 2007.

3.4 Phase 1d): Prototype Testing (10/06 – 12/06)

DaimlerChrysler has re-scheduled Phase 1 prototype testing to meet the revised timeline. Testing will take place between October and December of 2006.

3.5 Phase 1e): Technology Gap Analysis (06/05 – 01/07)

In September of 2005, the Team agreed to analyze five technology gaps, which were hindering mass reduction through the use of AHSS:

- Commercial availability of uncoated AHSS for chassis structures in the gage range of 1.6 to 2.8mm
- Forming of AHSS (hydroforming, stamping, extrusions)
- Welding of AHSS
- Strength and fatigue of AHSS joints
- Corrosion protection for steel <2.0mm thick

The original timeline called for the technology gap analysis to be completed by January of 2006. In hindsight, this date was unrealistic. Proper gap analysis depended on the lessons learned during fabrication and testing of the Phase 1 prototypes. In September of 2006, as part of setting a revised

Timeline (see Section 1.0), the Team implemented a major effort to summarize the lessons learned from Phase 1 by January of 2007. A summary of the work already completed or now underway follows:

Availability of AHSS. The Team is seeking a table showing the global availability of AHSS by grade, coating, and thickness. It has asked the American Iron and Steel Institute to present this request to the International Iron and Steel Institute.

Forming of AHSS. The Team pursued AHSS hydroforming as discussed in Section 3.2. Circle grid analysis was undertaken on DP 590 and TRIP780 parts in the Phase 1 prototypes. Tensile tests will be performed on the formed DP590 and TRIP780 parts in the Phase 1 prototypes. The A/SP Stamping Team has reviewed the formability for the stampings in the Preliminary Phase 2 Design. It is conducting a forming analysis on the four parts that it believes are the most difficult to form. The Stamping Team (see 2.T) is considering the Lightweight Chassis Structure Team's request to prepare Guidelines for AHSS Stampings (This Team has prepared Guidelines for HSS Stampings).

Welding of AHSS. The tubular siderails of the Phase 1 prototypes are made by butt welding an upper DP590 stamping to a lower DP590 stamping. Tensile tests were performed on the butt welds. Each weld in a Phase 1 prototype was sectioned. Micrographs of the sectioned welds have been examined (see Figure 6) and micro-hardness traverses are being prepared. A/SP's Joining Team (see 2.P) has provided its findings on arc welding processes for AHSS. The Team is dialoguing with

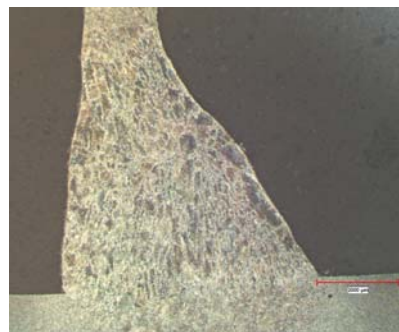


Figure 6. Micrograph of Phase 1 prototype weld.

A/SP's Joining Team and ORNL (see 5.C) on the properties and modeling of the HAZ in AHSS welds.

Strength and Fatigue of Joints. The Team is concerned that the mechanical properties in the HAZ of AHSS welds might be less than those of the parent steel. Hence, it is working with A/SP's Joining Team (see 2.P) and ORNL (see 5.C) to better understand this issue. Fatigue is also a concern. Presentations to the Team from A/SP's Fatigue Team have indicated that the fatigue strength of parent AHSS material is proportional to its tensile strength. However, the fatigue strength of welds in AHSS is the same as the fatigue strength in low-carbon materials. A/SP's joining Team has research underway to better understand the fatigue strength of arc welded AHSS.

Corrosion. Chassis Structures typically count on the thickness of the steel itself to provide long term corrosion resistance. Thus, there is likely some thickness below which adequate corrosion protection is not provided. As a rule of thumb, this thickness is 2.0mm. The Team has assembled a group of chassis corrosion experts (mainly from the OEMs) to investigate appropriate corrosion protection methods for thin AHSS members.

4.0 Phase 2: Design Optimization

4.1 Phase 2a): Benchmarking Study (11/05 – 3/06)

A/SP, in collaboration with the American Iron and Steel Institute (AISI), retained Dr. Alan Hine to conduct a benchmarking study. Dr. Hine assembled chassis structure data for 53 vehicles sold in North America from 2004 to 2006. The vehicles include small cars, mid-size standard cars, mid-size luxury cars, full-size luxury cars, SUVs and sports-specialty vehicles. For each of these vehicle categories, Dr. Hine identified (in his opinion) the best-in-class chassis structures. He presented the reasons and innovations, which led him to select the best-in-class chassis structures. The RFQ issued for Phase 2c) specified that the successful supplier would be required to analyze the Hine benchmarking data, summarize the lessons learned and apply them during the Phase 2 redesign.

4.2 Phase 2b): Topology Optimization (11/05 – 5/06)

A/SP retained Altair Engineering to mesh the solid volume of the baseline rear chassis structure and to conduct a series of topology runs to understand the topology that will best meet the system requirements.

For the final iteration of the topology optimization, Altair created a 3D mesh, which was used as the starting point for Phase 2c).

4.3 Phase 2c): Design/Process (12/05 – 3/07)

Through a clean sheet redesign and the use of lessons learned in Phase 1, the goal is to obtain a minimum mass reduction of 25% with no more than a 9% cost premium.

In December 2005, an RFQ to conduct Phases 2c) and 3 was sent to 19 companies. Seventeen companies submitted quotes. The Team reviewed the quotes and placed five companies on a short list (eta, Quantech, Martinrea, Cosma and Menard). These five companies were asked to a meeting to review their quotes. Individually, each company was asked to outline its technical approach, the amount of in-kind it would contribute to the project and its best price. As a result of the discussions, Martinrea International was selected in February, 2006 to conduct Phases 2a) and 3 at a cost of \$350,575. In early March, Martinrea submitted a detailed timeline for the work with the following milestones and completion dates:

- Milestone 1: Review 3 Design Footprints & Formulate Basic Design Structure (6/14/06)
- Milestone 2: Present 3 Design Alternatives for Review (7/19/06)
- Milestone 3: Kick-off Design for Prototype Parts (8/31/06)
- Milestone 4: MIT Cost Model (9/29/06)
- Milestone 5: Model Clean-up and Drawings (10/31/06)
- Milestone 6: Phase 2 Report Outs (12/22/06)
- Milestone 7: Phase 3 Report Outs (3/30/07)

Milestone 1: Three Design Footprints. On June 14, 2006, Martinrea presented six optional footprints with basic design structures. Martinrea also provided a ranking of the options as well as the pros and cons for each option. The Team selected three footprints for Milestone 2.

Milestone 2: Three Design Alternatives. On July 19, 2006, Martinrea presented three alternative designs (hybrid, stamped clamshell and tubular) as shown in Figure 7.

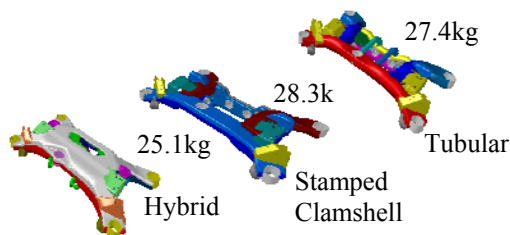


Figure 7. Three design alternatives.

A comparison between stress analysis results and stiffness results showed that the stiffness targets are harder to meet than the stress targets. The mass of all three alternatives exceed the target mass (21.9kg). However, mass may be reduced in Milestone 3 because many of the stiffnesses exceed the stiffness targets.

DaimlerChrysler conducted an initial cost review. All three alternatives are within the 9% cost premium target. On August 9, 2006, the Team selected the hybrid design for Milestone 3. It has the least mass and the most opportunity for stiffness optimization.

Milestone 3: Kick-off Design. On September 28, 2006, Martinrea presented the preliminary Phase 2 design as shown in Figures 8 to 11. The mass is 22.3kg versus the target mass of 21.9kg. There are 33 parts made from DP780, 350MPa HSLA and 245MPa low-carbon steel grades. Eleven parts are less than 2.0mm thick. As in the baseline chassis structure, the stress in some areas exceeds the yield strength. The key stiffness targets are met.

Although cost analysis is to be completed in Milestone 4, it appears that the cost will be less than the targeted 9% maximum premium.

Milestones 4 to 7. As indicated in Section 1.0, the Team revised the project timeline in September of 2006. Martinrea agreed to discontinue work on the project until the technology gap review is completed in January of 2007. At that time, Martinrea will resume the design activities per an agreed upon updated timeline and cost variance.

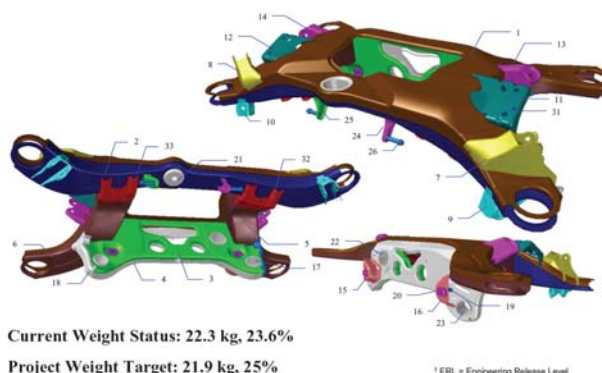


Figure 8. Preliminary Phase 2 design.



Figure 9. Preliminary Phase 2 design – exploded view.

4.4 Phase 2d): Phase 2 Prototype Build (4/07 – 6/07)

The fabrication of Phase 2 prototypes is scheduled for April to June of 2007. An RFQ for the prototype build will be issued early in April of 2007.

4.5 Phase 2e): Performance Testing (7/07 – 9/07)

DaimlerChrysler has scheduled Phase 2 prototype testing for July to September of 2007.

Item	Part Description	Qty	Material	Thickness (mm)
1	Upper Shell	1	DP780	1.7
2	Front Lateral Member - Lower Shell	1	DP780	2.2
3	Rear Lateral - Front Shell	1	DP780	1.6
4	Rear lateral - Rear Shell	1	DP780	1.7
5	Rear Longitudinal Lower - Left	1	DP780	1.7
6	Rear Longitudinal Lower - Right	1	DP780	1.7
7	Tension Link - Left	1	50 ksi	2.5
8	Tension Link - Right	1	50 ksi	2.5
9	Compression Link Bracket - Left	1	50 ksi	2.7
10	Compression Link Bracket - Right	1	50 ksi	2.7
11	Sta-Bar Bracket - Left	1	50 ksi	1.7
12	Sta-Bar Bracket - Right	1	50 ksi	1.7
13	Camber Link Bracket - Left	1	50 ksi	2.5
14	Camber Link Bracket - Right	1	50 ksi	2.5
15	Toe Link Bracket - Left	1	50 ksi	2.5
16	Toe Link Bracket - Right	1	50 ksi	2.5
17	Rear Closure Plate - Left	1	50 ksi	1.6
18	Rear Closure Plate - Right	1	50 ksi	1.6
19	Toe Link Sleeve	2	50 ksi	4.0
20	Toe Link Alignment Bracket	4	50 ksi	2.5

Figure 10. Preliminary Phase 2 design – bill of materials.

5.0 Phase 3: Communications (2/07 - 3/08)

A Communications Direction Sheet is being prepared by the Team. Communications of the Phase 1 results will begin in February 2006. The main communications for the Phase 2 results will be in the first quarter of 2008.

ⁱ Denotes project 601 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.

Z1. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Part 1: Formability, Weldability and Performance Evaluations of AHSS Parts for Automotive Structures

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Contractor: Pacific Northwest National Laboratory

Contract No.: DE-AC06-76RL01830

Objective

- Investigate the formability of advanced high-strength steel (AHSS), with emphases on loading temperature, loading paths and “secondary” deformation effects on part ‘residual’ strength and microstructure;
- Develop a fundamental understanding of transformation kinetics of AHSS steels by analyzing the crystallographical and morphological features of the phase transformations subject to different thermal and mechanical loading paths from forming and welding;
- Provide performance data and constitutive models for formed AHSS parts;
- Investigate the weldability of AHSS under various welding processes and parameter conditions applicable to auto production environment;
- Generate weld performance data including static strength, formability, impact strength, and fatigue life as function of welding processes and parameters;
- Investigate welding techniques for improved AHSS weld performance and benchmark the performance against the current welding practices for roll-formed and hydro-formed AHSS frame and underbody structure applications;
- Develop design guidelines on AHSS to assist rapid structure design and prototyping.

Approach

- Investigate formability and weldability of AHSS. This task includes: forming under complex loading paths (uniaxial and biaxial); quantification of formability and weldability for various grades of AHSS based on their chemistries and corresponding thermal-mechanical process;
- Investigate the interdependency of manufacturing processes: weldability of a formed part and formability of a welded part;
- Develop transformation kinetics model and macroscopic constitutive relationships for AHSS: dual-phase (DP), transformation-induced plasticity (TRIP), and complex phase (CP).
- Systematically evaluate the effects of various welding process and process parameters on the microstructure and property of welds. Welding processes include gas metal arc welding, laser welding, hybrid laser-arc welding,

and resistance spot welding. Metallurgical and process models will be used to analyze the microstructure evolution. The properties will be measured as a function of geometry, composition, process and process parameters. A performance evaluation procedure will be developed that allows for quantifying the performance improvement, weight and cost savings associated with use of AHSS.

- Evaluate structural performance of formed and welded parts made of AHSS. This task will provide the automotive design engineers with accurate material performance data for design verification of AHSS structural parts.

Recent Accomplishments

- Evaluated thru-thickness phase property variations.
- Completed a preliminary study to determine the required weld sizes in resistance spot welds of DP800 and TRIP800 steels under cross tension and lapshear loading.
- Completed high strain rate tests of TRIP800 at High Temperature Materials Laboratory (HTML) at ORNL.
- Completed quantification of retained austenite volume fraction under high rate deformation via modified X-ray diffraction technique.
- Finished initial feasibility study of using neutron source to quantify in-situ lattice strain partitioning during TRIP600 and TRIP800 deformation.

Future Direction

- Complete the quantification of retained-austenite volume fraction on TRIP steels under shear deformation.
- Conduct bi-axial loading under different temperatures and quantify phase evolution.
- Perform in-situ phase transformation and volume fraction measurement using neutron or synchrotron source.
- Improve the multi-phase self-consistent constitutive model.
- Perform meso-scale constitutive modeling using the concept of representative volume element under different deformation mode.
- Predict structural performance of formed part made of TRIP800 with and without updated material properties.
- Continue UHSS B-Steel weldability study.

Introduction

This project is a collaborative effort between the Department of Energy, Pacific Northwest National Laboratory, and the United States Automotive Materials Partnership (USAMP) of the U.S. Council for Automotive Research (USCAR). The work started in October 2005.

Because of their excellent strength and formability combinations, more and more advanced high strength steels (AHSS) are being used in vehicle body structures to reduce vehicle weight and improve vehicle crash performance. Currently, the technical barriers hindering wider applications of AHSS in the domestic auto industry include: 1) The fundamental behaviors of AHSS parts subject to different thermal and mechanical loading paths

(forming and welding) are not fully understood and quantified; 2) The constitutive behaviors for the formed parts are not available to CAE engineers for rapid prototyping; 3) Welding-induced complex microstructures and the effects of different welding processes and welding parameters on weld performance are not well understood. In order to address these technical barriers, this project examines key aspects of the manufacturing process that AHSS would be exposed to, and systematically evaluate how the forming and thermal histories affect final strength and ductility of the material. The goal is to provide the automotive design engineers with accurate material performance data for design verification of AHSS structural parts.

Base Metal Mechanical Property Characterization under Different Temperatures and Strain Rates

Base material properties for TRIP800 have been characterized under different OEM manufacturing temperatures ranging from -40°C to 93°C, as well as different strain rates ranging from 10⁰/sec (Refs. 1 and 2) to 400/sec. Transformation kinetics for material points undergone high rate deformation has been quantified using a modified X-ray diffraction technique. For example, Figure 1 shows the true stress versus strain curves for TRIP800 ASTM E8 sub-sized sample under 256 inch/sec dynamic loading. The results clearly indicate the temperature dependency of the TRIP steel dynamic performance. At room temperature, the total elongation is around 33%, similar to the quasi-static results. Under higher or lower temperature, however, TRIP800 has reduced ductility under dynamic loading. This observation has also been validated by high-rate digital images taken during the deformation process, see for example Figure 2.

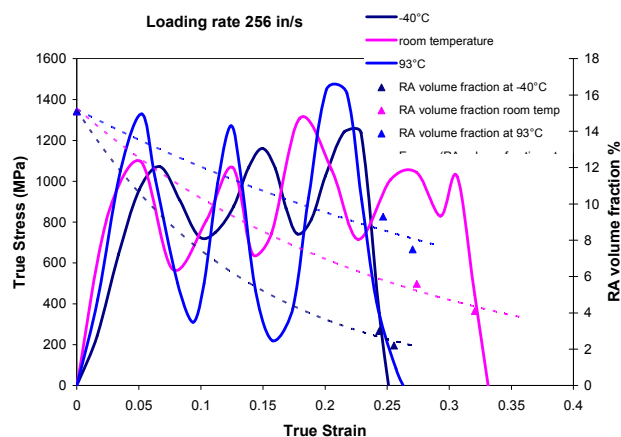


Figure 1. True Stress-Strain response of TRIP800 Steel at three different temperatures at ram velocity of 256 in/sec.



Figure 2. High-rate digital image of a sample right before fracture: deforming at 640 inch/sec under 93°C.

Thru-thickness Gradient of Phase Volume Fraction for As-received Sheet

The initial thickness of the steel was 1.55 mm. We reduced the sheet thickness to 1.42mm, 1.16 mm, 0.97 mm, and 0.77 mm. The 1.16 mm and 0.77 mm thickness correspond, respectively to 1/4 and 1/2 of the initial thickness. Figure 3 illustrates the thru-thickness phase variation for the material in as-received condition.

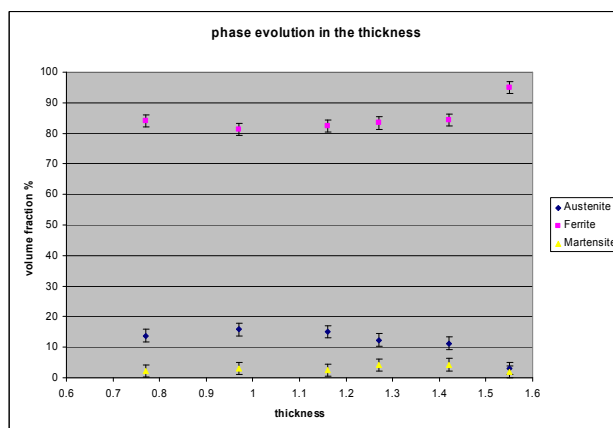


Figure 3. Thru-thickness phase variation of the as-received material.

A high gradient of retained austenite volume fraction exists near the sheet surface (1.55mm). This is likely due to the thermal-mechanical process undergone by the material to achieve its overall mechanical properties. In addition, there is a measurable amount of martensite in the as-received material, indicating the formation of martensite during the sheet manufacturing process. The thru-thickness phase variation leads to the thru-thickness variations of mechanical properties for the as-received sheet material. These thru-thickness property variations can lead to undesired forming behaviors such as shear fracture. More work in this area is underway to quantify the effects of thru-thickness property variations on sheet local formability/bendability.

In-Situ Lattice Strain Partitioning for TRIP Steel during Deformation

The in-situ lattice strain data were obtained by the Rietveld analysis of the measured diffraction spectra at Los Alamos National Laboratory. See Figure 4 for TRIP590 as an example. As the applied stress increases, the tensile internal stress develops in the retained austenite (FCC) in the axial direction (L), while compressive stress builds up in transverse direction (T). The strain partitioning is initially uniform among the two phases until a stress level of 300 MPa. Above this stress level, austenite phase is taking up considerably more strain than its BCC matrix, likely going through phase transformation and provide additional transformation strain. At the applied stress level of ~550 MPa, austenite starts to diminish. As the austenite phase exhausts, the martensite phase continues to take up more strains in the longitudinal direction as expected.

Retained austenite volume fractions for deformed samples are also measured at Argonne National Laboratory using the Advanced Photon Source by high energy X-ray. Figure 5 shows the schematic of the test setup, and Figure 6 illustrates the measured change of volume fraction of FCC and BCC as well as texture for the deformed (12% strain) and undeformed (as-received) samples.

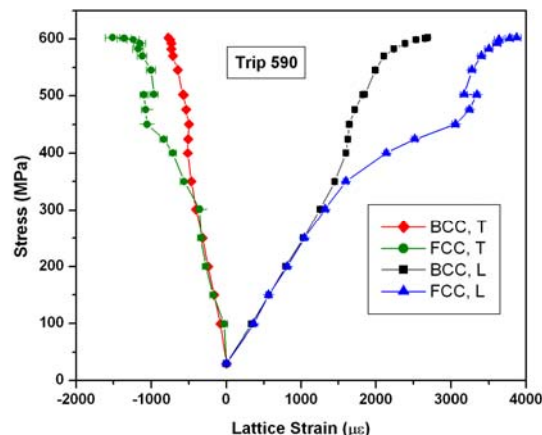


Figure 4. The lattice strain evolution of both retained austenite (FCC) and martensite (BCC) in TRIP590 steel during the in-situneutron measurements in SMARTS (Spectrometer for Materials Research at Temperature and Stress).

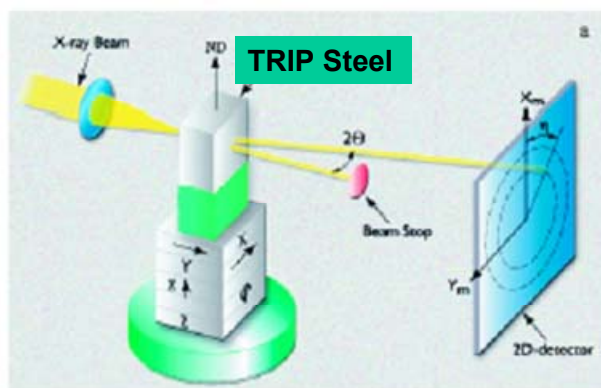


Figure 5. Schematic of test set up at APS.

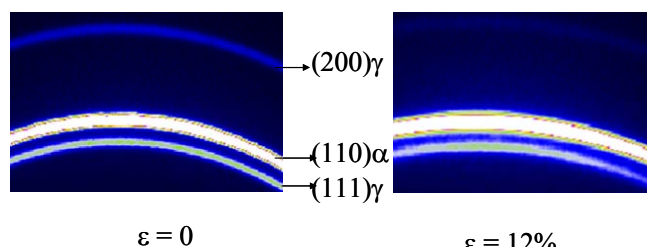


Figure 6. Part of Debye rings illustrating the change of volume fraction for deformed and un-deformed samples.

Resistance Spot Welds (RSW) of DP800 and TRIP800- Effect of Critical Fusion Zone Size for Lapshear Samples

The effects of spot weld fusion zone size on failure modes, static strength, and energy absorption of DP800 and TRIP800 have been studied. Both cross tension and lapshear coupon configurations have been used (Ref. 3). See Figures 7 and 8. Under cross tension loading condition, it was found that

- The conventional weld size guidance of $4\sqrt{t}$ is not sufficient to produce nugget pullout failure mode for both DP800 and TRIP800 resistance spot welds.
- Analytical limit load based model together with micro-hardness measurements can be used to predict the critical fusion zone sizes for both DP800 and TRIP800.
- At the critical fusion zone level, both interfacial fracture and nugget pullout can be observed. Even though both failure modes offer similar distributions in terms of peak load, nugget pullout provides much higher energy absorption level than the interfacial fracture mode.
- Below the critical fusion zone sizes, interfacial fracture is the dominant failure mode with large load scatter and poor energy absorption. Above the critical fusion zone size, nugget pullout is the dominant failure mode with tightly controlled peak load and energy absorption distributions. Further increasing the fusion zone size beyond the critical size will not bring about linearly increased weld performance in terms of peak load and energy absorption.

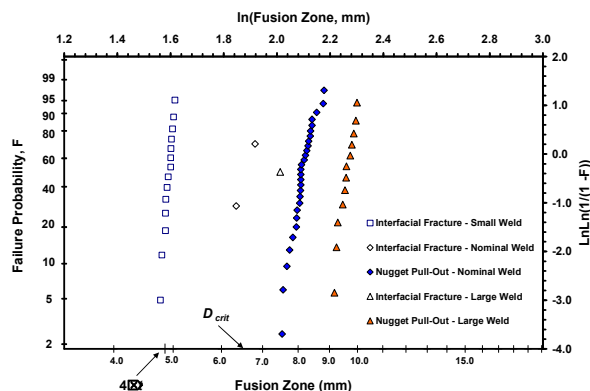


Figure 7. Fusion zone size distribution and its effect on failure mode for TRIP800 under cross tension.

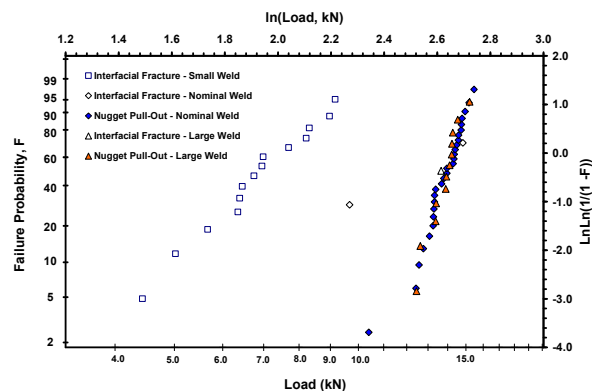


Figure 8. Peak load distributions for three weld populations in TRIP800 under cross tension.

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Presentations/Publications/Patents

1. Sun X, EV Stephens, and MA Khaleel. Effects of Fusion Zone Size on Failure Modes and Performance of Advanced High Strength Steel Spot Welds." In SAE World Congress 2006.
2. Sun X, EV Stephens, and MA Khaleel. Effects of Fusion Zone Size on Failure Modes and Performance of Advanced High Strength Steel Spot Welds." Accepted for publication in the research supplement of the Welding Journal, 2006.
3. Sun X, EV Stephens, MA Khaleel and Z. Feng. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Formability, Weldability and

Performance Evaluations of AHSS Parts for Automotive Structures. Presentation at USAMP AMD 2006 Sheet and Forming Offsite Meeting, Oct, 2006. Southfield, MI.

4. Feng, Z. and X Sun. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Formability, Weldability and Performance Evaluations of AHSS Parts for Automotive Structures. Presentation at USAMP AMD 2006 Welding and NDE Offsite Meeting, Nov. 2006. Southfield, MI.

Z2. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Task 2 - Weldability and Performance Evaluations of AHSS Parts for Automotive Structures

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Contract No.: DE-AC05-00OR22725

Objective

- Develop fundamental understanding and predictive capability to quantify the effects of welding and service loading on the structural performance of welded AHSS auto-body structures.
- Investigate the weldability of AHSS under various welding processes and parameter conditions applicable to auto production environment.
- Investigate welding techniques and practices to improve AHSS weld performance and benchmark the performance against the current welding practices.
- Generate weld performance data including static strength, impact strength, and fatigue life as function of welding processes/parameters, and steel grade and chemistry.
- Develop design guidelines and CAE methodology to assist rapid structure design validation and prototyping of AHSS parts, to achieve maximum vehicle weight reduction through intelligent selection and utilization of AHSS based on the fitness-for-purpose principle.

Approach

- Conduct comparative welding experiments on various AHSS including HSLA, dual-phase (DP), and transformation-induced plasticity (TRIP) boron steel to develop the correlation among the joint properties, welding process conditions, and steel chemistry.
- Characterize and rank the factors controlling the weld geometry, weld microstructures and weld joint performance.
- Develop an integrated thermal-mechanical-metallurgical welding process and performance modeling methodology to accurately predict the microstructure and mechanical property gradients in the weld region; use the experimental data to validate the integrated model.

Accomplishments

- Generated baseline gas metal arc weld performance data (static tensile strength and fatigue life) for a number of AHSS including HSLA590, DP600, DP780, DP980, TRIP780, M130, M220 and Boron Steels.
- Proposed two design parameters (normalized static joint strength and joint efficiency) to quantify the benefit of AHSS under static loading conditions.
- Established the strong correlation between weld joint efficiency and the HAZ softening under static loading condition.
- Revealed the dependency of weld fatigue life as function of steel grade and chemistry.
- Determined the negligible influence of HAZ softening on the weld fatigue life.
- Demonstrated the feasibility of improved weld fatigue life through adjustment of welding conditions.

Future Direction

- Continue to identify key factors controlling the weld joint performance under static and fatigue loading conditions.
- Investigate the weld joint performance under impact loading conditions.
- Develop the integrated thermo-mechanical-metallurgical modeling framework.
- Investigate welding techniques and practices to improve weld fatigue performance.
- Develop design guideline and CAE analysis methodology to assist rapid design and prototyping of AHSS structures.

Introduction

This project is part of joint research at Oak Ridge National Laboratory (ONRL) and Pacific Northwest National Laboratory (PNNL) on “Characterization of Thermo-Mechanical Behaviors of Advanced High-Stress Steels (AHSS).” This joint program aims at developing fundamental understanding and predictive modeling capability to quantify the effects of auto-body manufacturing processes (forming, welding, paint baking, etc) and in-service conditions on the performance of auto-body structures made of AHSS. ORNL’s research (designated as Task 2 in this joint program) focuses on welding of AHSS. In late part of the program, the interdependency of manufacturing processes – weldability of a formed part and formability of a welded part, will be investigated.

The automotive industry is aggressively pursuing insertion of AHSS in automotive body structures for crashworthiness and weight reduction. However, welding AHSS for automotive structure applications presents some unique technical challenges to the steel suppliers and end-users. Data available so far have indicated that welding AHSS with practices developed for the conventional mild steels may not

be the preferred approach to bring the full benefits of AHSS. Because of their higher carbon and alloying element contents, AHSS as a whole are more sensitive to the thermal cycle of welding than mild steels. Consequently, the weld region of AHSS generally exhibits greater variations in microstructure and mechanical properties that are highly dependent on welding conditions and type of steel. As the properties of AHSS often require an orchestrated optimization of steel chemistry control and advanced steel processing route by steel maker, the microstructure changes in the weld region often result in different performance characteristics than the optimum base metal microstructures. As higher grades of AHSS (DP800, boron steel, TRIP 780 and above) are being developed and available for auto-body applications, the property degradation penalty due to welding is more profound, and must be adequately dealt with by both the steel makers and auto end-users.

It is important to recognize that the steel chemistry and steel processing route are only two of the many variables that govern the performance (static strength, fatigue life, impact properties, etc) of a weld joint in an auto structure. The geometric

features of a weld (such as the weld surface profile and weld size) also play an important role. Furthermore, the welding processes and parameters need to be selected carefully to match the metallurgical characteristics of a given AHSS; and different types of AHSS may require different welding conditions to realize the benefits of the steels.

To the end-users, making the strongest weld is certainly desirable. However, the real engineering challenge is more than that it seeks to answer the question of “how to specify a weld to meet the target performance specifications of a welded component in the most cost-effective way”. It involves more than merely selecting the “best” steel in the market – in many cases, the specification could be met by using a less-expensive steel together with intelligent specification and control of weld geometric attributes and welding conditions, to achieve the total cost-effectiveness. It would be highly desirable if the quality and performance characteristics of the AHSS welds could be accurately specified in the design stage, resulting in significant cost-savings and shortening of the design cycle.

The goals of this program are two-fold. First, it is to develop a fundamental understanding of the welding effects on the microstructure and the associated property changes in AHSS weld joints, and to develop the predictive capability that quantitatively relate these microstructure and property changes to the steel chemistry and welding process conditions. With the developed fundamental understanding, we also seek new welding techniques and practices to improve the structural performance of AHSS welded auto-body components. Second, it aims at addressing the weldability and performance of AHSS from the end-user’s perspective by developing a systematic approach that enables the product design engineers to reliably and cost-effectively design AHSS welds, to meet the performance design targets of welded components. In this aspect, we plan to consolidate the effects of welding on AHSS into weld performance data and design guidelines or CAE design methodology, which take into account of the weld property variations and the best-in-class welding practices, for use in the design stage to achieve vehicle weight reduction through intelligent selection and utilization of various AHSS

This research will focus on welding of AHSS for chassis and underbody applications. The proposed work scope includes both seam welds in making the hydroformed and roll-formed tubes, and attachment welds for assembling parts. The effects of welding process and parameters on the microstructure and property of welds will be systematically evaluated. Welding processes under consideration are gas metal arc welding (GMAW), laser welding, and resistance spot welding (RSW). The microstructure evolution will be studied by means of advanced materials characterization techniques. Metallurgical and process models will be used to analyze the microstructure evolution. The weld performance properties will be measured as a function of weld geometry, steel composition, welding process and process parameters. A performance evaluation procedure will be developed that allows for quantifying the performance improvement, weight and cost savings associated with use of AHSS. At the end of program, guidelines to design and quantify weld performance for AHSS automotive structure applications will be delivered.

FY 2006 was the first year of this program. The research in FY2006 focused on obtaining the baseline knowledge and understanding about the static strength and fatigue life of AHSS welds. To this end, we investigated a wide range of AHSS types and grades most interesting to the US automotive industry.

We started the program with a series of discussions and meetings with auto OEMs and steel suppliers to refine the program work scope for the next 12 to 18 months. This work scope was developed based on the research needs and issues facing the automotive industry in application of AHSS and the availability of AHSS from steel suppliers. We also met with the A/SP Joining Technologies Team to discuss the goals and research plan of this program, and to have a better understanding of various welding and high-strength steel programs under A/SP. We agreed to meet with the A/SP Joining Technologies Team on a regular basis for information exchange and update of research progress. Recently, the interactions with A/SP have been expanded to other A/SP committees such as the Sheet Steel Fatigue Team and the Lightweight Chassis Structures design team.

From these interactions, an industry advisory committee was formed for this program which consisted of representatives from the Big-Three (DaimlerChrysler, Ford and GM), and five steels suppliers (Mittal Steel, US Steel, Severstal, AK Steel, Dofasco).

Steels

Steels selected for the study included five types of AHSS: high-strength low-alloy (HSLA), dual-phase (DP), transformation induced plasticity (TRIP), martensite, and boron steel. In addition, mild steel was used as the baseline steel for comparison. The steel selection matrix also included different surface conditions: uncoated (Bare), hot-dipped galvanized (GI), and hot-dipped galvanized (GA) coatings.

The FY2006 research concentrated on 2-mm thick steels. Eventually, the program will expand to thicknesses ranging from 1.5 to 8.5 mm, which would cover the typical materials thicknesses for passenger vehicles, light trucks, and SUVs. The heavier gauge steels used in light trucks and SUVs may offer the biggest light-weighting opportunities. According to the automotive industry, the light trucks and SUV currently use less AHSS in the body structures than the passenger sedans. Furthermore, for the same percentage gauge reduction, a heavy gauge section would offer more absolute weight reduction than a thin gauge section.

The program received strong support from the steel suppliers. So far, a total of 22 grade-gauge-coating steel combinations were received from six steel companies: Mittal Steel, US Steel, AK Steel, Dofasco, Severstal, and ThyssenKrupp. They are listed below:

- Group 2 (350 MPa ~500 MPa)
 - 1.5mm HSLA Bare
 - 1.5mm Mild Steel Bare (2 suppliers)
 - 2.0mm DR210 Bare
- Group 3 (500 MPa~ 800 MPa)
 - 2.0mm DP600 Bare
 - 1.8mm HFT590 Bare, 1.6mm 590R GA, 1.8mm DP590Bare
 - 1.7mm DP600 HDGI, 1.6mm DP600 GA, 2.0mm DP600 HDGI
 - 2.0mm HSLA590 Bare
- Group 4 (>800 MPa)
 - 1.4mm DP780 GI, 1.6mm DP780 EG, 2.0mm DP780 Bare
 - 1.5mm TRIP780 GA
 - 1.5mm Boron HT Bare, 1.5mm Boron UHT Bare, 2.0mm Boron HT Bare, 2.0mm Boron UHT Bare
 - 2.0mm DP980 Bare
 - 2.0mm M130 Bare, 2.0mm M220 Bare

We will continue to work with the OEMs and steel suppliers to obtain additional heavier gauge materials for future studies.

Welding

Based on the input from the industry, it was decided that the FY06 and part of FY07 activities would focus gas metal arc welding (GMAW), since it is the commonly used joining process for attachment welds and structure welds for heavy gauge underbody and chassis assembly parts. The selection of GMAW process also considered the fact of on-going studies on resistance spot welding and other welding processes in the USCAR program.

All welds were made in the lap joint configuration, the most common type of weld for attachment and structure joining with the GMAW process. All welds were fabricated with a robotic system (OTC Robot Almaga) at AET-Integration, Inc.

ER70-S3, a filler metal commonly used by the auto industry, was used in this study. This filler metal may present a strength under-match for some higher strength AHSS, i.e., the tensile strength of weld metal is lower than that of the base metal. However, as shown in later part of this report, the degree of under-match was not sufficient to cause failure in the weld metal. All welds investigated so far failed outside the weld metal, either in the base metal or the heat-affected zone (HAZ). This was due to the fact that the “structural” strength of a lap joint not only depends on the weld metal strength, but also on the weld geometry that can greatly influence the stress distribution in the weld region (weld metal and HAZ).

In order to evaluate the intrinsic microstructural differences in the weld region of different AHSS, all welds were made with the same welding heat input

level. In keeping the same sheet thickness, same joint configuration and same welding heat input in our experiments, all weld joints would experience the same welding thermal history. Therefore, the microstructure differences in the weld region in this study can be solely attributed to the chemistry of different steels. The potential complications of steel phase transformation behavior in welding due to different thermal histories can be avoided in our comparative study

Welding parameters representative to current practices in the automotive industry were adopted in the study. Specifically, the welding speed, which controls the welding productivity, was set at 50 in/min. The welding current and voltage were 230A and 24V, respectively. Other process parameters such as welding torch angle, etc, were adjusted to obtain a consistent weld profile (toe angle and radius, etc.) for different steels. Figure 1 shows the weld profiles of different AHSS produced with the above baseline welding parameters.

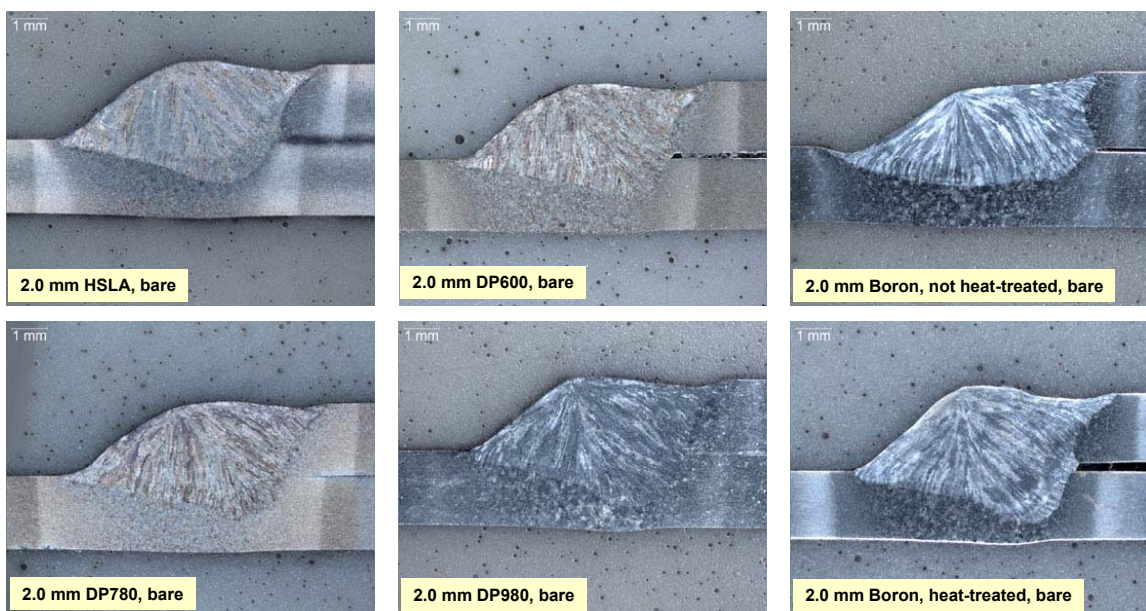


Figure 1. Cross-section view of weld profiles among different AHSSs.

Maintaining consistent weld profile was an important consideration in evaluating the performance of different steels. It minimizes the complications of weld stress variations due to weld geometry differences. By maintaining consistent welding thermal history and weld stress profile, it was then possible in this study to correlate the weld structural performance (static strength and fatigue life) to the intrinsic microstructural differences in the weld region of different steels.

It is noted that the welding conditions used in our comparative study may not be optimal for AHSS. The welding process improvement/optimization for AHSS will be an important direction of our future research in this program

Results and Discussions

Static Tensile

Figure 2 summarizes the static tensile testing results of 11 different steels. For each type of steel, the ultimate tensile strength of both the lap joint weld and the base metal are provided. In the figure, the steels are arranged based on their base metal strength. Note that the base metal strengths shown in the figure are the actual measured values from the tensile test, and they are higher than those in the steel specification. This reflects a common practice of steel suppliers to ensure their products meet or exceed the minimum specified values for a given steel designation.

As shown in Figure 2, as the base metal strength increases, the lap joint weld strength generally increases. The benefits of AHSS (in terms of static tensile strength) over mild steels can be measured by the normalized static joint strength (NSJS) – the ratio of the static weld strength of AHSS to that of

the baseline reference mild steel (DR210 in this case). For example, DP780 steel has a NSJS of 209%, which means its static tensile strength is about twice that of DR210. Among all AHSS studied so far, the boron steel has the highest NSJS, about 2.5 times of that of DR210.

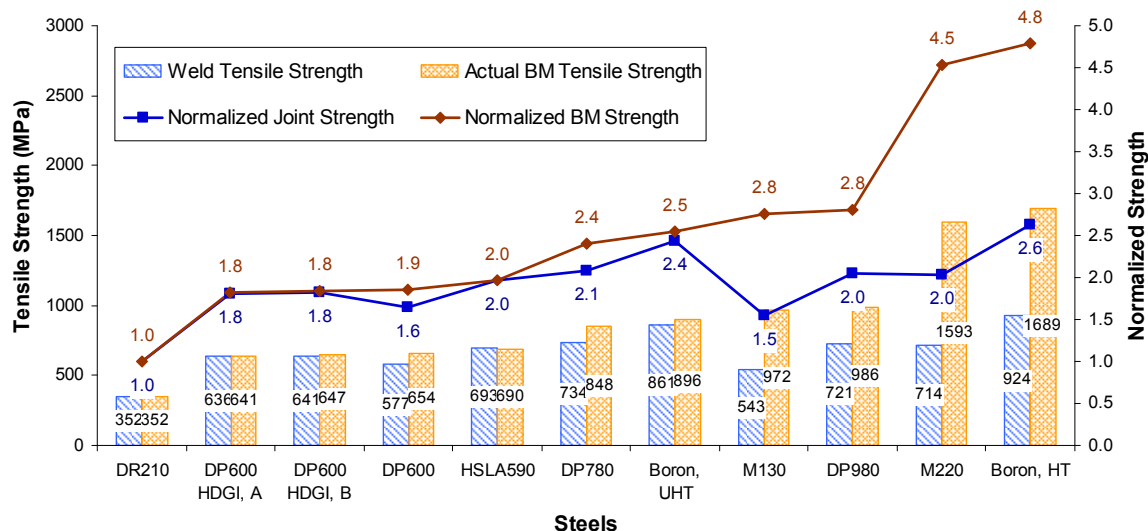


Figure 2. Comparison of lap joint static tensile strength and base metal tensile strength among different AHSS. All steel sheets were 2.0mm. The joint strength is normalized to that of DR210 (baseline reference mild steel).

NSJS can be considered as a measure for weight reduction potential of high-strength steel in replacing the mild steel while maintaining the same static joint tensile strength.

It is important to note that NSJS of AHSS does not always follow the increase in base metal strength. As shown in Figure 2, for steels on the low strength end of AHSS spectrum (DP600, DP780, and HSLA590 in this study), the weld joint strength is about the same as the base metal steel. This means that welding does not adversely penalize the strength gains of these types of AHSS. On the other hand, for steels with primarily martensitic base metal microstructure (DP980, M130, M200, heat-treated hardened boron steel), the static strengths of the lap welds are considerably lower than those of the base metal. For example, for the hardened boron steel, its base metal tensile strength (1689MPa) is 4.8 times of DR210's (352MPa). However, its weld joint strength (924MPa) is only 2.5 times higher. This means that the microstructure changes in the weld

region caused by the thermal cycles of GMAW could severely diminish the potential gains of static tensile strength of these steels.

The degree of welding induced penalty to the static tensile strength of AHSS can be measured by the joint efficiency (JE). JE is defined as the ratio of the weld strength to the base metal strength of the same steel. The joint efficiencies of the 11 steels studied in this program are given in Figure 3. For the steels investigated in this program, AHSS with nominal tensile strength below 800MPa (the Group 3 AHSS) maintains relatively high joint efficiency (minimal welding induced penalty). On the other hand, higher strength Group 4 AHSS (800MPa and above) exhibit considerable joint efficiency reduction. This drop in joint efficiency is caused by the significant microstructure changes in the HAZ (HAZ softening), as revealed by the microhardness measurement.

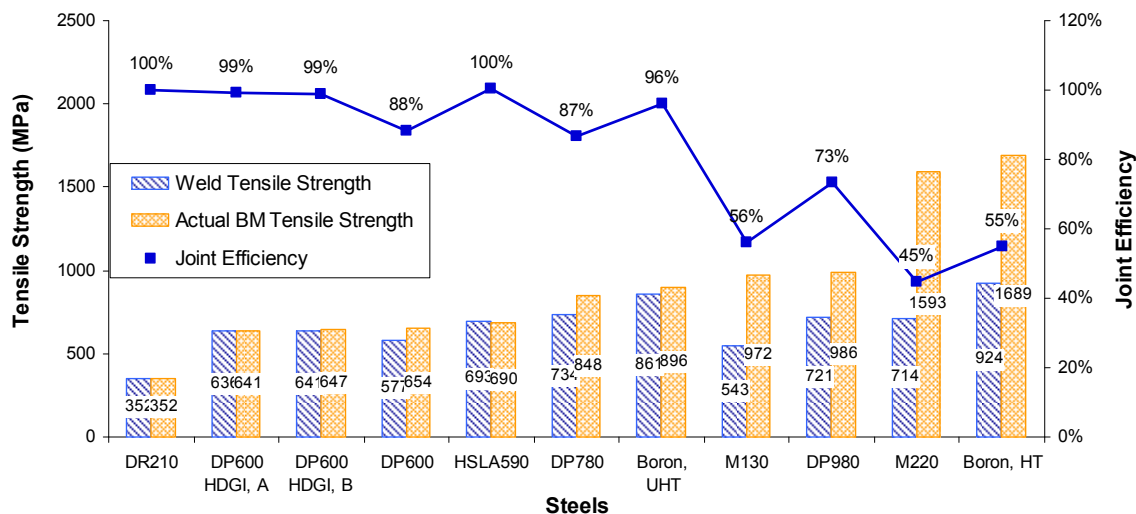


Figure 3. Joint efficiency of different AHSS. The joint efficiency is the ratio of weld strength to the base metal strength. Steel sheet thickness: 2.0mm.

HAZ Softening

Microhardness mapping was performed to better understand the microstructural changes in the weld region. The microhardness map was constructed from 6000 to 8000 automated microhardness

measurements with spatial resolution of 0.15 to 0.2 mm, and covers the different regions of a weld joint (weld metal, HAZ, and adjacent unaffected base metal). Figure 4 presents the microhardness distribution of the hardened boron steel weld.

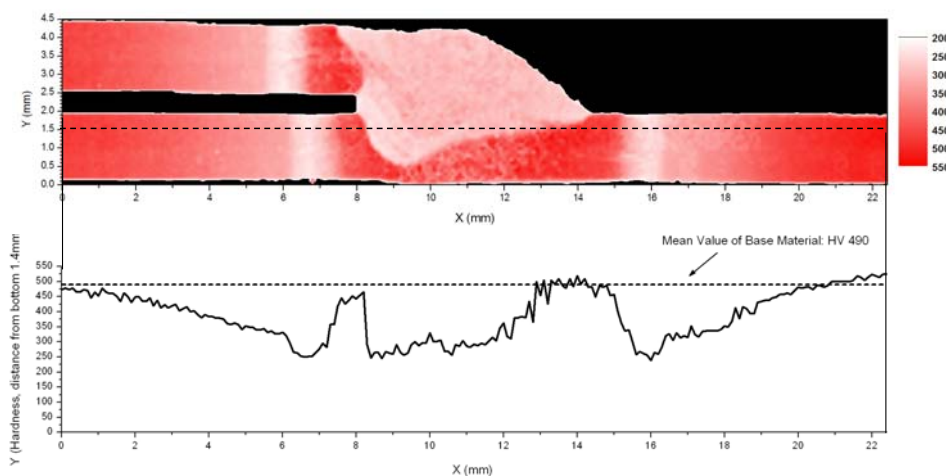


Figure 4. Weld region microhardness mapping of hardened boron steel. The line plot is taken along the dashed line in the microhardness map.

The boron steel weld exhibits highly non-uniform microhardness distribution. Considerable softening (as low as 45% of the base metal hardness) occurs in the intercritical region of the HAZ that is about 1-mm away from the weld fusion line. Because of the high hardenability of boron steel, the coarse grain HAZ adjacent to the fusion line transforms

back to martensitic microstructure on cooling, thereby essentially recovering to the hardness of the base metal which also has martensitic microstructure.

Figure 5 compares the microhardness distributions in three AHSS: HSLA590, DP980 and hardened

boron steel. For comparison purpose, the microhardness of each weld was normalized with respect to its mean base metal microhardness. A normalized value of 1.0 in the plot means the hardness is the same as the base metal. The normalized microhardness maps clearly reveal the different degrees of HAZ softening of the three AHSS. The low-strength grade HSLA590 shows minimal HAZ softening. DP980 exhibits a

noticeable level of HAS softening: a wide softening region with hardness only about 65% of the base metal DP980. The ultra-high strength boron steel develops the most severe HAS softening. The minimum hardness in the softening region was only about 45% of the base metal value. The drastic differences in joint efficiency of different AHSS can be related to the extent of HAZ softening in these steels.

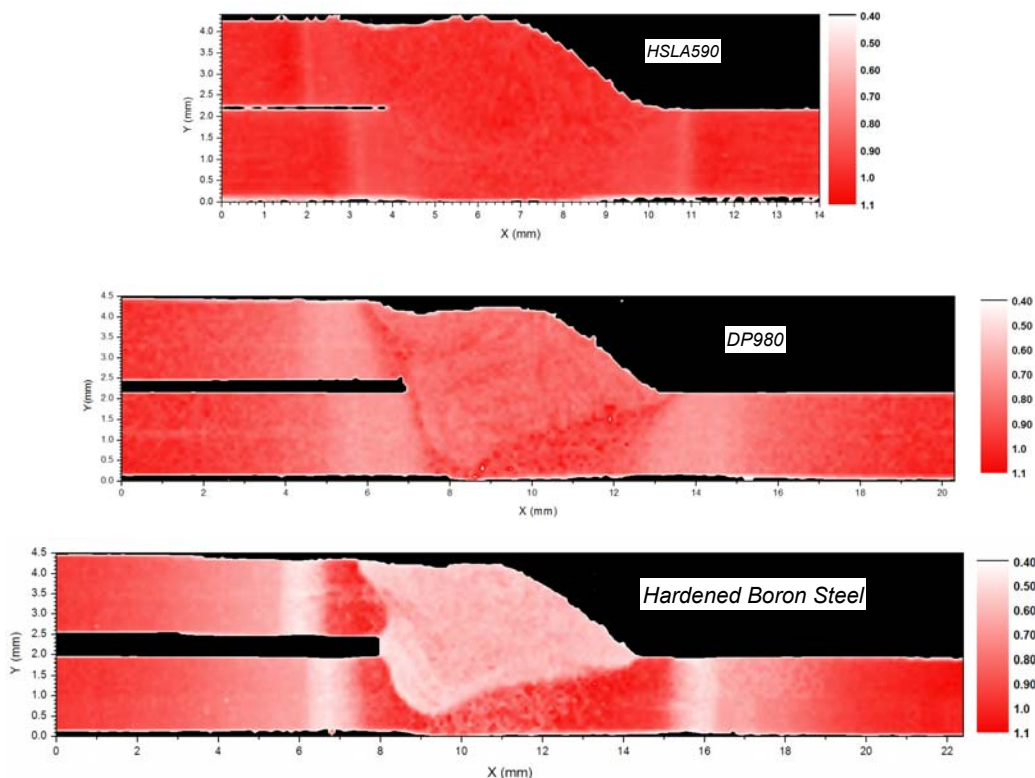


Figure 5. Comparison of microhardness distributions in three AHSS. The microhardness has been normalized with respect to the respective base metal microhardness. Mean base metal hardness: HSLA 590: 240Hv; DP980: 280Hv; Hardened boron steel: 490Hv.

Correlation between Static Tensile Strength and HAZ Softening

Figure 6 shows the failure locations of 6 AHSS welds during the static tensile test. As the base metal strength increases, the failure location generally shifts from the root of the weld (where geometric stress concentration exists) to the softened region in HAZ where the materials strength decreases. Such shifting in failure location correlates well to the observed joint efficiency reduce

tion of the ultra-high strength steels (DP980, boron and martensitic steels) showing in Figure 3.

Figure 7 provides the side-by-side comparison of the failure location and the microhardness distribution in DP90 steel. Clearly, the DP90 weld failed in the softened region in HAZ. Therefore, the weld-strength of the ultra high-strength steels is governed by the softened region in HAZ, not by the base metal strength.

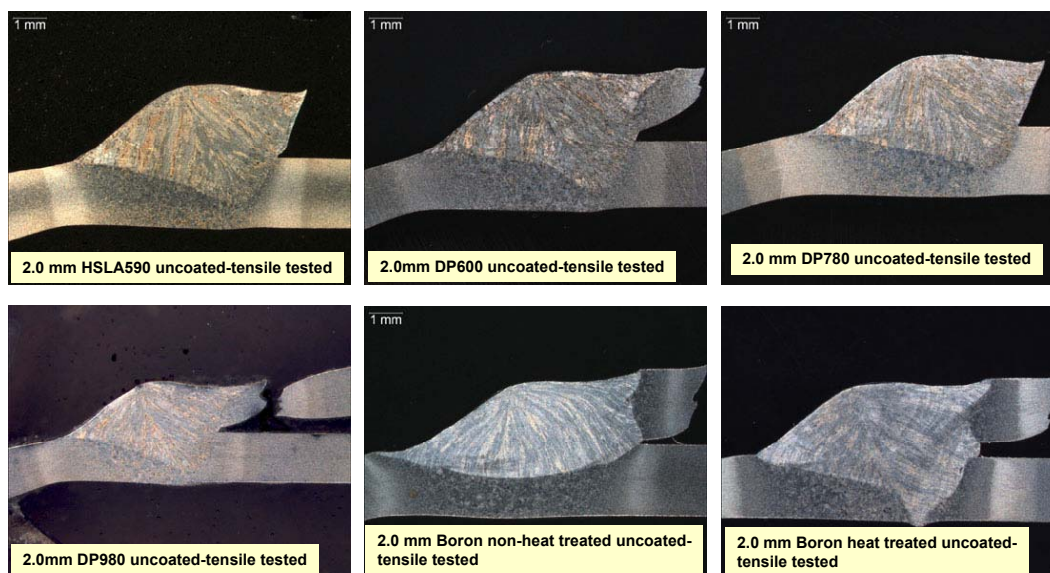


Figure 6. Failure locations of AHSS weld under static tensile loading.

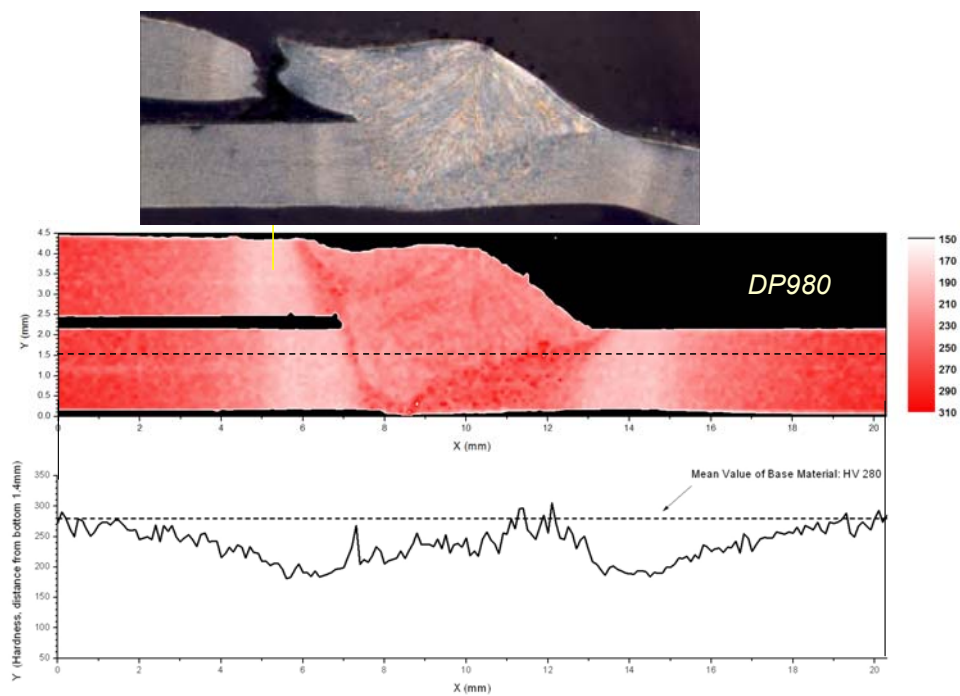


Figure 7. Failure location during static tensile loading correlates to HAS softened region in DP980.

Fatigue Life of AHSS Weld

Figure 8 compares the lap weld fatigue lives of 9 different uncoated AHSS: heat-treated hardened boron steel (Boron HT), unhardened boron steel (Boron UHT), two martensitic steels (M220 and M130), three DP steels (DP980, DP780, DP600), HSLA590, and DR210. The fatigue tests were

conducted in constant load amplitude mode ($R=0.1$). For clarity, only the statistical regression lines were plotted. There are noticeable differences in fatigue lives among the different steels. For example, at 100MPa nominal stress range, the mean fatigue life of DR210 weld is about 8 times longer than that of the hardened boron steel weld.

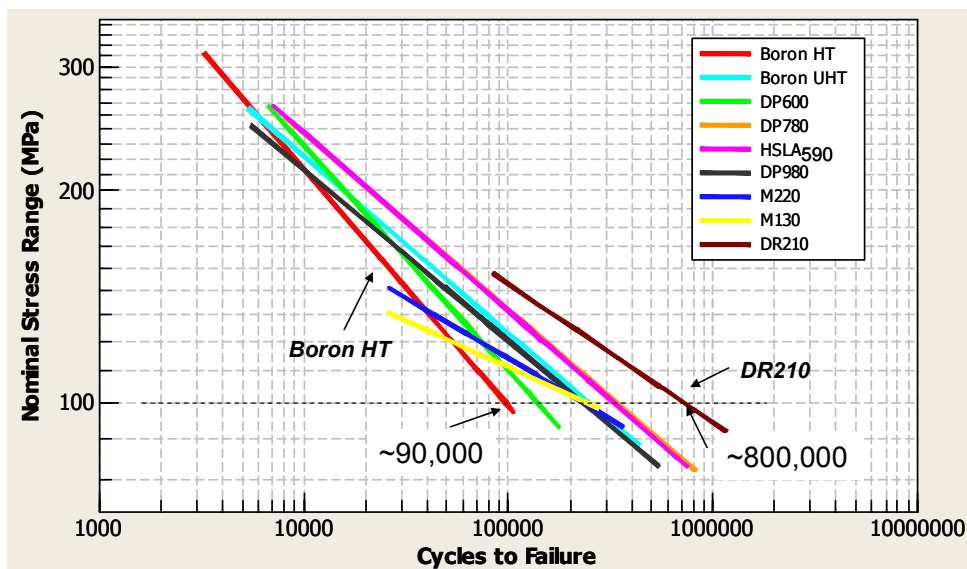


Figure 8. Comparison of fatigue S-N curves of different AHSS made under same welding conditions and having consistent weld profile. The regression curves are shown. $R=0.1$. Steel sheet thickness: 2 mm.

Figure 9 shows the failure locations of 6 different AHSS during the fatigue test. Contrary to the static tensile loading case, the fatigue failure initiated either at the weld toe or weld root, and none

was in the softened region of HAZ. This suggests that the HAZ softening does not contribute to the fatigue crack initiation and propagation (thereby the fatigue life), at least for the steels investigated so far.

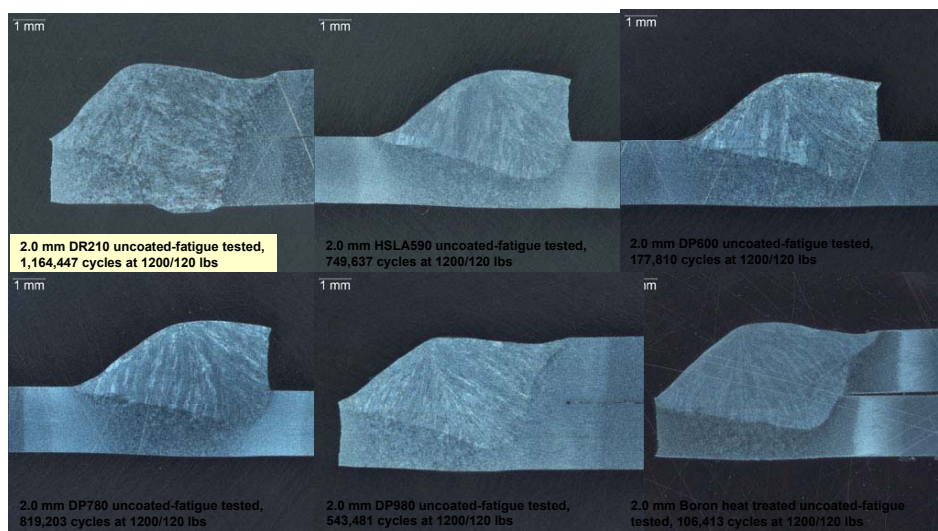


Figure 9. Failure locations in fatigue testing.

Finally, Figure 10 shows our preliminary attempts to improve the fatigue life of AHSS welds. By reducing the welding speed from 50 in/min to 40 in/min (still within the welding speed window commonly accepted by the industry) and maintaining the same welding heat input, the fatigue life of DP600 increased over 20 times. The fatigue

life of the DP600 weld made with the baseline welding condition was among the worst of all the steels investigated (see Figure 8). The improved welding practice resulted in fatigue life far better than the best weld (DR210) made with the baseline welding condition.

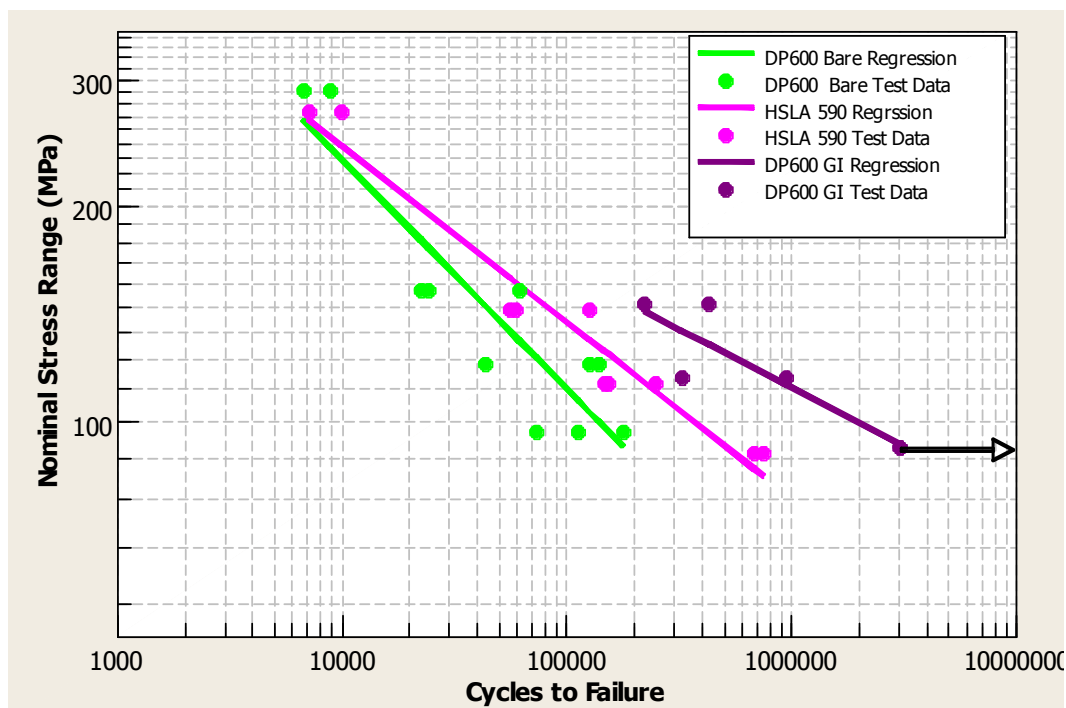


Figure 10. 20X improvement in fatigue life of DP600 steel. Both the regression lines and the actual testing data are shown. DP600 Bare and HSLA 590 were made at the baseline.

We will further investigate the fundamental causes/mechanisms leading to the above drastic fatigue life improvement in FY2007 and FY2008 to determine whether they are related to the weld profile changes, the microstructural changes, or both. If the microstructure is an important factor, then what type of microstructure would lead to better fatigue life? More detailed modeling analysis, microstructure characterization and additional special welding tests are planned in FY2007 and FY2008 to understand the key factors controlling the weld fatigue life.

Conclusions

In FY2006, the first year of the program, we have developed baseline knowledge about the static tensile strength and fatigue life of GMAW lap weld

joints for a wide range of AHSS (HSLA, DP, TRIP, martensitic, and boron steels). It was found, for the steels and welding conditions investigated herein, that:

1. The static tensile strength of GMAW lap weld increases as the base metal steel strength increases. However, the joint efficiency decreases considerably for ultra-high strength steels (DP980, boron and martensitic steels) due to the profound HAZ softening in these steels. The lower grade AHSS without HAZ softening maintains their high joint efficiency.
2. Steel grade dependency of weld fatigue life has been confirmed. The HAZ softening does not appear to be a major factor influencing the weld fatigue life.

3. It is feasible to drastically improve the weld fatigue life of AHSS by manipulating welding process conditions. The fundamental causes/mechanisms leading to the observed fatigue life improved require further investigation.

Presentations/Publications/Patents

None in FY2006, but several presentations and publications have been accepted in FY2007.

APPENDIX A: ACRONYMS AND ABBREVIATIONS

2DTBC	two-dimensional triaxially-braided composite
2D-WAXS	two-dimensional wide-angle x-ray scattering
3D	three-dimensional
A/SP	Auto/Steel Partnership
ABS	acrylonitrile-butadiene-styrene
ACC	Automotive Composites Consortium
ACD	after concept design
ACDC	after concept design analysis check
ADCB	asymmetric double-cantilever beam
AF	anisotropy factor
AFM	atomic-force microscope(y)
AFO	after final optimization
AFS	American Foundry Society
AHSS	advanced high-strength steel
AISI	American Iron & Steel Institute
AKDQ	aluminum-killed draw-quality
Al	aluminum
ALM	Automotive Lightweighting Materials
AMD	Automotive Metals Division
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
AO	after optimization
AP	acidification potential
APC	American Plastics Council
APGE	Arizona Proving Grounds Exposure
ARA	(International) Automotive Recycling Association
ARC	(International) Automobile Recycling Congress
ASTM	American Society for Testing and Materials
ATR	attenuated total reflection
AWS	American Welding Society
BCC	body center cubic
BDE	brominated diphenyl ethers
BET	Brunauer-Emmett-Teller
BFO	before final optimization
BH	bake hardenable
BIW	body(ies)-in-white
BL	black liquor
BLRT	bond-line read-through
BO	before optimization
BOF	body-on-frame
BSEF	Bromine Science and Environmental Forum
BT	bond-line thickness
BW	bond width
CAABS	crash analysis of adhesively bonded structures
CAD	computer-aided design

CAE	computer-aided engineering
CANMET	an R&D entity of the Minerals and Metals Sector of Natural Resources Canada
CB	cylinder block
CCD	charge-coupled device
CCHT	combinatorial, combi, high-throughput
CCT	cosmetic corrosion test
CDA	critical damage area
CF	carbon fiber
CFSI	carbon fiber systems integration
CLTE	coefficient of linear thermal expansion
CMM	coordinate measuring machine
CMOS	complementary metal oxide semi-conductor
COM	Conference of Metallurgists
CP	cold pressed / complex phase
CPU	central processing unit
CRADA	Cooperative Research and Development Agreement
CrN	chromium nitride
CRTM	compression resin-transfer molding
CT	compact tension / computerized tomography
CTE	coefficient of thermal expansion
CWT	Changing World Technologies
CZ	cohesive zone
DC	direct current
DCB	double cantilever beam
DCX	DaimlerChrysler
DCZM	discrete cohesive zone model
DFEP	Die Face Engineering Project
DH α MS	dihydroxy- α -methylstilbene
DIC	digital image correlation
D-LFT	direct long-fiber thermoplastic
DMA	dynamic mechanical analysis
DOE	Department of Energy
DoE	design of experiment
DP	dual phase
DP800	Dual Phase 800
DQ	drawing quality
DQSK	drawing-quality special-killed
DRIFT®	Direct Reinforcement Fabrication Technology
DSC	differential scanning calorimetry / dispersion-strengthened copper
DTA	differential thermal analysis
DTUL	deflection temperature under load
DW	driven wedge
ECD	electron capture detector
EDS	energy-dispersive spectrometer(ry)
EDX	energy-dispersive X-ray analysis
EF	(thermal-drilling) extension factor
EH&S	environmental, health and safety.
ELV	end-of-life vehicle(s)
EMF	electromagnetic forming

EP	eutrophication
EPA	Environmental Protection Agency
ERW	electric resistance welding
FCC	face-centered cubic
FCD	final concept design
FCVT	FreedomCAR and Vehicle Technologies
FE	finite element
FEA	finite-element analysis
FEC	front engine cover
FE/CV	finite-element/control volume
FEM	finite-element method/modeling
FGPC	Future Generation Passenger Compartment
FLD	fiber-length distribution or forming-limit diagram
FMBEM	Fast Multipole Boundary Element Method
FMVSS	Federal Motor Vehicle Safety Standard
FOP	fully-oxidized polyacrylonitrile
FP2	focal project 2
FP-3	focal project-3
FRP	fiber-reinforced plastic
FSSW	friction-stir spot welding
FSW	friction-stir welded
FTC	Federal Trade Commission
FT-IR	Fourier transform infrared
FY	fiscal year
GA	Galvaneel
GaBi	Ganzheitliche Bilanzierung
GC	gas chromatography
GC/MS	gas chromatography/mass spectroscopy
GC-ECD	gas chromatography and electron-capture detector
GDIS	Great Designs in Steel
GF	glass fiber
GI	galvanized coating
GM	General Motors (Corporation)
GMAW	gas metal arc weld
GMT	glass-mat thermoplastic
GPEC	Global Plastics Environmental Conference
GPRA	Government Performance and Results Act of 1993
GWP	global warming potential
HAZ	heat-affected zone
HBA	hydroxybenzoic acid
HDG	heavy-duty galvanized / hot-dipped galvanized
HDPE	high-density polyethylene
HI-MAC	High-Integrity Magnesium Automotive Casting
HIPS	high-impact polystyrene
HNA	hydroxy-naphthoic acid
HPDC	high-pressure die casting
HSBS	hot-stamp(ed) boron steel
HSLA	high-strength low-alloy

HSS	high-strength steel
HTML	high-temperature materials laboratory
ICME	integrated computational materials engineering
IDDRG	International Deep Drawing Research Group
IF	interstitial free
IFU	University of Stuttgart
IIHS	Insurance Institute for Highway Safety
IISI	International Iron & Steel Institute
IP	instrument panel
IR	infrared
ISRI	Institute of Scrap Recycling Industries
ISV	internal state variable
ITP	International Titanium Powder (Inc.)
JCI	Johnson Controls, Inc
LBNL	Lawrence Berkeley National Laboratory
LC	liquid crystallines
LCM	liquid composite molding
LDH	limited dome height
LDPE	low-density polyethylene
LFT	long-fiber-reinforced injection-molded thermoplastics
LIMS	Liquid Injection Molding Simulation
LPPM	low-pressure permanent-mold
LW	laser-welded
LWB	laser-welded blanks
LWFS	lightweight front-end structure
MAP	microwave-assisted plasma
Mart	martensitic
MFE	magnesium front end
MFEDD	magnesium front end design and development
MFERD	magnesium front end research and development
MFR	melt flow rate
MHD	magnetohydrodynamic
MI	melt index
MIG	metal inert gas
Missu	Mississippi State University
M-K	Marciniak-Kuczynski
MLPD	magnesium low-pressure development
MMB	mixed-mode bending
MMV	multi-material vehicle
MOST	Ministry of Science and Technology (China)
MPCC	magnesium powertrain cast component
MS	martensitic steels / mass spectroscopy
MSS	mean/maximum shear strength
MTT	Materials Technical Team (FreedomCAR)
MW	Mead Westvaco
MWV	MeadWestvaco (Corporation)

N/D or N.D.	Not detected
NA	North America(n)
NANO	new application of nano obstacles
NC	numerical control
NCAP	New Car Assessment Program
NCC	National Composites Center
NCC-ET	North Carolina Central Campus—Emerging Technologies
NDE	non-destructive evaluation
NDI	non-destructive inspection
NEXAFS	near-edge x-ray absorption fine structure
NIST	National Institute for Standards and Technology
NMR	nuclear magnetic resonance
NSF	National Science Foundation
NSJS	normalized static joint strength
NTRC	National Transportation Research Center
NVH	noise, vibration, and harshness
OC	Owens Corning (Corporation)
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
P/M	powder metallurgy
P4	programmable powdered preform process
PAN	polyacrylonitrile
PBDEs	polybrominated diphenyl ethers
PBT	polybutylene terephthalate
PC	polycarbonate
PCBN	polycrystalline cubic boron nitride
PCBs	polychlorinated biphenyls
PDE	partial differential equation
PE	polyethylene
PEY	partial electron yield
PI	principal investigator
PMC	polymer-matrix composite
PNNL	Pacific Northwest National Laboratory
POCP	photochemical ozone creation potential
PP	polypropylene
PP/PE	polypropylene/polyethylene
PPM	parts per million
PPO	polyphenylene oxide
PPS	post-peak softening
PS	polystyrene
PSC	Project Steering Committee
PTC	Project Technical Committee
PTT	Phan-Thien Tanner
PU	polyurethane
PVC	polyvinyl chloride
R&D	Research and Development
RFQ	request for quotes
RIS	radiographic inspection standards

RPM	revolutions per minute
RSC	rear seal cover / reduced strain closure
RSW	resistance spot-welding
RTM	resin-transfer molding
RUC	representative unit cell
RVE	representative volume element
RWD	rear-wheel drive
SAE	Society of Automotive Engineers
SAMPE	Society for the Advancement of Materials and Process Engineering
SCMD	structural cast magnesium development
SD	standard deviation
SDSM&T	South Dakota School of Mines and Technology
SEA	specific energy absorption
SEM	scanning electron microscope(y)
SERR	strain-energy release rate
SFT	short-fiber-reinforced injection-molded thermoplastics
SG	specific gravity
SLB	single-leg bend
SLC	sub-liquidus casting
SMARTS	Spectrometer for MATerials Research at Temperature and Stress
SMC	sheet molding compound
SNL	Sandia National Laboratories
SOCs	substances of concern
SOP	standard operating procedure / structural oil pan
SORPAS	Simulation and Optimization of Resistance, Projection and Spot Welding Processes
SOW	statement of work
SRF	strain reduction factor
SRI	Southern Research Institute
SRIM	structural reaction-injection molding
SSM	semi-solid metal
ST	schapery-like, thermodynamically-based theory
SUV	sport utility vehicle
SWE	spot-weld element
SWSG	structural weld sub-group
TBD	to be determined
TC	transcrystalline region
TDM	Troy Design and Manufacturing
TFF	thread-forming fastener
TGA	thermo-gravimetric analysis
ThD	thermal drilling
TLCP	thermotropic liquid-crystalline polymer
TMAC	Test Machine for Automotive Crashworthiness
TMS	The Minerals, Metals, and Materials Society
TPI	Troy Polymers, Inc.
TPO	thermoplastic olefins
TP-P4	thermoplastic P4
TRIP	transformation-induced plasticity
TS	tensile strength
TTSP	time temperature superposition principle

TWB	tailor-welded blank
TWT	tailor welded tube
TYE	tensile, yield and elongation properties
UAB	University of Alabama-Birmingham
UD	unidirectional
UDRI	University of Dayton Research Institute
UEL	used-defined element
UHMW	ultra-high molecular weight
UHSS	ultra high strength steel
ULC	ultra-large casting
ULSAB-AVC	Ultralight Steel Auto Body-Advanced Vehicle Concepts
UPA	units per annum
UPE	unsaturated polyester
USAMP	United States Automotive Materials Partnership
USCAR	United States Council for Automotive Research
USPTO	United States Patent and Trademark Office
UT	University of Tennessee
UTK	University of Tennessee, Knoxville
UTS	ultimate tensile strength
UV	ultraviolet
VARTM	vacuum-assisted resin-transfer molding
VE	vinylester
VPB	viscous pressure bulge
VRP	Vehicle Recycling Partnership
VUMAT	vectorized user material
VW	Volkswagen
W25Re	25 wt% rhenium
WDS	wavelength-dispersive spectrometer(ry)
Wpm	welds per minute
XFEM	extended finite-element method
XRD	x-ray diffraction
YAG	yttrium-aluminum-garnet
YS	yield strength

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