United States Automotive Materials Partnership LLC (USAMP)

Department of Energy (DoE)

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Projects from January 1, 2002 through January 31, 2011

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Key to Company Names

Due to industry consolidations and mergers over the duration of the Cooperative Agreement, several names of corporations have changed as reflected in the table below:

Previous Name	Present Name
Alcan	Rio Tinto Alcan
Bethlehem Steel	ArcelorMittal
Chrysler Corporation DaimlerChrysler	Chrysler Group LLC
Dofasco	ArcelorMittal
General Motors Corporation	General Motors Company General Motors Holdings LLC
Ispat Inland Steel	ArcelorMittal
National Steel Corporation	US Steel
Rouge Steel Company	Severstal, North America Inc.
Stelco	US Steel
UES Inc.	ESI North American
Volvo (division of Ford Motor Company)	Volvo

Executive Summary

The United States Automotive Materials Partnership LLC (USAMP) was formed in 1993 as a partnership between Chrysler Corporation, Ford Motor Company, and General Motors Corporation. Since then the U.S. Department of Energy (DOE) has supported its activities with funding and technical support. The mission of the USAMP is to conduct vehicle-oriented research and development in materials and materials processing to improve the competitiveness of the U.S. Auto Industry. Its specific goals are:

- To conduct joint research to further the development of lightweight materials for improved automotive fuel economy.
- To work with the Federal government to explore opportunities for cooperative programs with the national laboratories, Federal agencies such as the DOE and universities.

As a major component of the DOE's Office of FreedomCAR and Vehicle Technologies Program (FCVT) collaboration with the USAMP, the Automotive Lightweighting Materials (ALM) program focuses on the development and validation of advanced materials and manufacturing technologies to significantly reduce automotive vehicle body and chassis weight without compromising other attributes such as safety, performance, recyclability, and cost. The FCVT was announced in FY 2002 and implemented in FY 2003, as a successor of the Partnership for a New Generation of Vehicles (PNGV), largely addressed under the first Cooperative Agreement.

This second USAMP Cooperative Agreement with the DOE has expanded a unique and valuable framework for collaboratively directing industry and government research efforts toward the development of technologies capable of solving important societal problems related to automobile transportation. USAMP efforts are conducted by the domestic automobile manufacturers, in collaboration with materials and manufacturing suppliers, national laboratories, universities, and other technology or trade organizations. These interactions provide a direct route for implementing newly developed materials and technologies, and have resulted in significant technical successes to date, as discussed in the individual project summary final reports.

Over 70 materials-focused projects have been established by USAMP, in collaboration with participating suppliers, academic/non-profit organizations and national laboratories, and executed through its original three divisions: the Automotive Composites Consortium (ACC), the Automotive Metals Division (AMD), and Auto/Steel Partnership (A/SP). Two new divisions were formed by USAMP in 2006 to drive research emphasis on integration of structures incorporating dissimilar lightweighting materials, and on enabling technology for non-destructive evaluation of structures and joints. These new USAMP divisions are: Multi-Material Vehicle Research and Development Initiative (MMV), and the Non-Destructive Evaluation Steering Committee (NDE).

In cooperation with USAMP and the FreedomCAR Materials Technical Team, a consensus process has been established to facilitate the development of projects to help move leveraged research to targeted development projects that eventually migrate to the original equipment manufacturers (OEMs) as application engineering projects. Research projects are assigned to one of three phases: concept feasibility, technical feasibility, and demonstration feasibility. Projects are guided through ongoing monitoring and USAMP offsite reviews, so as to meet the requirements of each phase before they are allowed to move on to the next phase. As progress is made on

these projects, the benefits of lightweight construction and enabling technologies will be transferred to the supply base and implemented in production vehicles.

The single greatest barrier to automotive use of lightweight materials is their high cost; therefore, priority is given to activities aimed at reducing costs through development of new materials, forming technologies, and manufacturing processes. The emphasis of the research projects reported in this document was largely on applied research and evaluation of mass savings opportunities through the aggressive application of lightweight materials, advanced computational methods, and the demonstration of production capable manufacturing processes intended for high-volume applications, all directed towards the FreedomCAR Program goals. Priority lightweighting materials include advanced high-strength steels (AHSS), aluminum, magnesium, titanium, and composites such as metal-matrix materials, and glass- and carbon-fiber-reinforced thermosets and thermoplastics. Besides developing valuable new design and material property information, several projects have extensively used computer-based product modeling and simulation technologies to optimize designs and materials usage while addressing the cost-performance issues.

The purpose of this Summary Final Closeout Report is to document the successes, degree of progress, technology dissemination efforts, and lessons learned.

1. Structural Automotive Components from Composite Materials (ACC007)

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- Ford Motor Company
- Continental Structural Plastics
- Multimatic Engineering
- Chrysler Group, LLC

Project Duration: October 2006 – Present

1.1 Executive Summary

ACC007 encompasses two components: an underbody and a seat, as well as the materials and processes necessary for these components. The objectives of this project are:

- To guide, focus, and showcase the technology research of the four ACC working groups (Materials, Processing, Joining, and Energy Management).
- To design and fabricate structural automotive components with reduced mass and cost, and with equivalent or superior performance to existing components.
- To develop new composite materials and processes for the manufacture of these high-volume components.

The underbody sub-project will design, analyze, and fabricate a structural composite underbody, and assemble it into a donor vehicle structure. The underbody will contribute to the overall vehicle stiffness, and will also carry crash loads.

This is part of the USAMP Multi-Material Vehicle (MMV) Initiative, and will follow the MMV goals for cost and mass when they are established. The primary research outcomes expected of this project are:

- A 2 ½ minute cycle time (assuming 100K vehicle per annum, two-shift operation).
- Methods of joining and assembly of the underbody to the vehicle.
- Processes for fabricating oriented reinforcement within the time window.

The seat sub-project focuses on a second row seat which will combine the functions of a seat (both with and without an integrated restraint system) and a load floor. It must fold for the load floor, save mass, and be cost competitive at volumes from 20-300K. The primary research outcomes expected of this project are:

- Parts integration of structural and appearance parts, including the seat back, load floor structures and the load floor appearance.
- Hard point design for belt attachments, pivot points, and head restraint attachments.
- Processes for fabricating localized areas of oriented reinforcement in localized areas within the time window. However, the manufacturing process steps for the seat will likely be different from the underbody, so that while the solutions to this issue will have some synergy for the two components, there will also be significant differences.

1.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

1. Underbody sub-project

Phase I – selection of the materials and processes for the underbody, based on manufacturing considerations, compatibility with MMV goals, and a technical cost model analysis.

- Phase I of the project has been completed, with a glass fabric sheet molding compound selected as the primary material and process system.

Phase II – full design of the underbody.

- Phase II is also complete, and included the full design of the underbody including tooling, and development of the materials and processes. This will also include design of joining and assembly processes and evaluation of the durability of the materials.

Phase III – fabrication and testing of the underbody assembled into a suitable structure, in both static and crash. The tooling has been completed and the molding trials are underway.

2. Seat sub-project

Phase 1 – design and topology optimization for computer-aided engineering and comparator seat teardown and testing.

- Design and analysis of the ACC seat structure has been completed.
- Cost modeling of the ACC seat design and a comparator TPP4 design has been completed. A weight save of approximately 30% has been achieved, but is cost prohibitive due to the reliance on carbon fiber.

Phase II – design for and build of prototype seats and subsequent testing to validate the design, including crash testing.

- Build and test a composite front-end as a means of evaluating the various dynamic models.

1.3 Deliverables/Products Developed

- None at this time.

1.4 Technology Transfer Activities

1.4.1 Proprietary Reporting

- Presentations at ACC and USAMP Offsites.

1.4.2 Non-Proprietary Publications and Proceedings

[1] Berger, L., “A Structural Composite Automotive Underbody,” Society for the Advancement of Materials and Processing Engineering, Seattle, WA, May 17-20, 2010.

[2] Berger, L., “Design and Fabrication of a Structural Composites Automotive Underbody,” Society of Plastics Engineers Automotive Composites Consortium, Troy, MI, September 15-16, 2010.

[3] Berger, L. et al., “Properties and Molding of a Fabric SMC for a Structural Composite Underbody,” Society of Plastics Engineers Automotive Composites Conference and Exhibition, Troy, MI, September 15-16, 2010.

[4] Dove, C., “Shear Deformation Properties of Glass-Fabric Sheet Molding Compound,” Society of Plastics Engineers Automotive Composites Conference and Exhibition, Troy, MI, September 15-16, 2010.

[5] Fuchs, H. and Conrod, B., “Super Lap Shear Joint Structural Test-Analysis Correlation Studies,” Society of Plastics Engineers Automotive Composites

Conference and Exhibition, Troy, MI, September 15-16, 2010.

[6] Fuchs, H. and Deslauriers, P., "Double Dome Structural Test-Analysis Correlation Studies," Society of Plastics Engineers Automotive Composites Conference and Exhibition, Troy, MI, September 15-16, 2010.

[7] Shah, B. et al., "Structural Performance Evaluation of Composite-to-Steel Weld Bonded Joint," Society of Plastics Engineers Automotive Composites Conference and Exhibition, Troy, MI, September 15-16, 2010.

[8] Fuchs, J. et al., "Automotive Structural Joint and Method of Making Same," U.S. Patent Application 12/119084, May 12, 2008, Notice of claims approval May 27, 2010.

[9] Fuchs, J. et al., "Dynamic Load Bearing Composite Floor Plan for an Automotive Application," U.S. Patent 7784856, August 31, 2010.

[10] Berger, L. et al., "Materials and Processes for a Structural Composite Underbody," Society for the Advancement of Materials and Process Engineering, Memphis, TN, 9/802008.

[11] Fuchs, H., "Initial Design of the Automotive Composites Consortium Structural Composite Underbody," Society of the Advancement of Materials and Process Engineering, Memphis, TN, 9/802008.

[12] Berger, L., "Development of a Structural Composite Underbody," Society of Plastics Engineering Automotive Composites Conference, Troy, MI, September 16, 2008.

[13] Berger, L. and Fuchs, H., "Development of a Structural Composites Underbody," Society of Plastics Engineering Automotive Composites Conference, Troy, MI, September 16, 2008.

2. Development of Manufacturing Methods for Fiber Preforms (ACC040)

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- DaimlerChrysler Corporation
- Owens Corning
- National Composite Center
- MSX International
- Aplicator System
- Michigan State University
- 2Phase Tech
- Fortafil Fibers
- Hexcel
- Ontario Die Company
- Bartech
- Polywheels
- Applicator System AB
- Swiss Fed Institute
- Saint-Gobain Vetrotex
- Excel Pattern Works
- Global Tech International
- Meridian Automotive System
- NVH Solutions
- Delsen Testing Laboratories, Inc
- ERIM

Project Duration: January 2002 – December 2007

2.1 Executive Summary

It is generally acknowledged that a key to the large-scale application of liquid molded composite materials in the automotive industry is the successful development of improved fiberglass preform processes. Historically, fiberglass preforming has generally been done using either a conventional directed fiber process or a thermoformable continuous strand mat. The conventional directed fiber process has the advantage of using low-cost roving as the input material, but does not provide the quality, design freedom, high-volume capability and environmental "friendliness" needed for the automotive industry.

This project has focused on the development of the programmable powder preforming process (P4), a fully-automated robotic process, and its demonstration in the ACC Focal Project II pickup truck box program. A prototype manufacturing cell with two stations was designed, fabricated and installed at the National Composites Center in Kettering, OH. Optimized spray patterns for pickup box preforms, areal density consistency, net-edge quality and desired cycle times were demonstrated. Several generations of improved glass fiber and binder products have been identified.

The extension of this technology to manufacture carbon-fiber preforms is in progress at original equipment manufacturers to support the development of ultra-lightweight structures. Carbon-fiber requirements to permit rapid processing while achieving desired composite performance levels are being identified to provide guidance for fiber manufacturers to develop new products. Opportunities to extend automated preforming technology to make a preform containing a thermoplastic matrix, which can be consolidated to form the final part are being explored. Methods to achieve rapid orientation of reinforcing fibers are being investigated. Advances in preforming technology were further demonstrated in the structural automotive parts designed and prototyped as part of the ACC Focal Project III.

2.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Development of the P4 process on the ACC's preforming machine was conducted as part of Focal Project II. The carbon-fiber preforming effort supported ACC Focal Project III.

The initial pickup box robotic routines developed for preliminary testing and equipment buy-off were not sufficient to fabricate preforms within design specifications. Total preform glass loading was at 85% of the specified due to glass "wiping" and preform loft issues. Variability within particular sections of the pickup box preform was as high as ±50% due both to part geometry effects (top and bottom of ribbed sections) and robotic glass deposition routines. The net-shape/size characteristics of the preform were not adequately developed to avoid trimming and/or race tracking during molding.

ACC040 accomplishments are listed below:

1. Robotic program development was performed by members from the ACC, Aplicator System AB, and Owens Corning. During robotic programming, a basic programming theory for P4 preforming was developed. Several computer tools and spray pattern models were developed and utilized to achieve an optimum robotic glass deposition routine. Following completion of the robotic glass deposition programming, several improvements over the original pickup box preform were realized:
    - Total perform glass density at 100% of specification
    - Preform to preform weight variation: ±2%
    - Preform variability within specification (±12%)
    - Net-edge definition improved.

2. The ACC's Focal Project II tailgate was selected as a demonstration component for the P4 process. The slurry preforming process was originally selected to produce random fiber preforms for Focal Project II tailgates. However, due to the high areal density variability (greater than ±30%) within the preform, it was determined that the process was inadequate for random fiber tailgate preform production. Based on the areal density distribution demonstrated on the truck box preform using P4, it was also selected as the process to develop random fiber tailgate preforms for Focal Project II. Development of tailgate preforms will enhance the understanding of the process and allow information developed in the truck box preforming effort to be transferred to additional components.

3. Robotic glass deposition routines for the Focal Project II tailgate inner and outer preforms have been completed, however the overall preform has not yet been optimized. Preform optimization is currently being performed on both the tailgate inner and outer. Optimization efforts include areal density distribution, net-edge definition and cycle time. Areal density distribution will first be optimized to ensure the part is within design specifications. Following this task, net-edge definition will be performed to provide net shape preforms for the molding operation. Cycle time optimization will then be performed to minimize the glass deposition cycle while maintaining areal density distribution and net shape characteristics.

4. *Evaluation of carbon fiber in P4 process*—All of the carbon-fiber rovings tested failed to meet the ACC carbon-fiber roving specification and were also determined to be unsuitable for high-volume applications due to preform processing issues. Unfortunately, the material form has not improved significantly and processing of all available materials remains somewhat of an issue. Successful development of carbon-fiber rovings will depend upon extensive R&D at

the carbon-fiber suppliers to produce rovings to specifications. Currently, carbon-fiber roving development at suppliers is minimal and ”off-the-shelf” materials are not suitable for chopped fiber processing are being supplied. Unless funding of development programs at carbon-fiber manufacturers can be realized, advanced carbon fibers for chopped fiber applications will not be developed in a timely manner.

5. A full-scale P4 preforming machine was designed, fabricated, and refined for the prototype production of pickup truck box preforms for the ACC’s Focal Project II. This work has demonstrated that the P4 process has the capability to produce handleable, net-shape/net-size preforms that exhibit low within-part and part-to-part areal density variation. It has also shown that P4 is a highly automated process capable of rapid cycle times and low scrap rates.

6. Significant improvements have been made in the P4 process leading to increased processing capability and superior preform characteristics. Process controls, raw materials, preform characteristics including glass distribution and net-shape/size have all been vastly improved during the ACC’s P4 process development efforts.

P4 carbon-fiber preforming on the ACC’s preforming machine is currently an ongoing effort with new materials being developed and tested. The ACC will continue to develop and evaluate new carbon rovings in an effort to develop an improved low-cost carbon-fiber roving suitable for use in the P4 process with the current chopper gun.

Problems Encountered:

Current carbon-fiber materials are tows or single-ended rovings ranging from 1-320K. These carbon-fiber tows have traditionally been used in fiber conversion processes such as weaving, braiding, stitch bonding, and pre-pregging or in composite fabrication processes such as pultrusion and filament winding but not in chopping applications. Glass fiber is available in the same single-ended product form and is used in the same processes as listed above, however, an entirely different product form is used for chopping applications. Applications such as traditional spray-up, conventional directed-fiber preforming, sheet molding compound and P4 preforming use the glass roving product form. However, this product form is not available in carbon fiber at this time. Due to this gap in the available carbon product form, a new product must be developed for chopping type processes if carbon fiber is to be successfully utilized in high-volume applications. These product forms are currently under development with various carbon-fiber suppliers.

It is the intention to develop low-cost, polyacrylonitrile-based carbon-fiber rovings that exhibit processing characteristics similar to the currently available glass fiber rovings. This will allow a seamless substitution of materials into current high-volume composite processes.

In addition to the processing issues previously identified, several other items need to be investigated when chopping carbon fiber. Chopper blade wear could prove to be an issue when chopping carbon at high speeds. Various blade materials and blade coatings are currently being investigated to optimize blade performance, chopping characteristics, blade wear, and cost. The current material handling system may also need to be examined to optimize processing of carbon strands. Tensioning pulleys, contact surfaces, and eyelets are all areas that are currently being investigated.

2.3 Deliverables/Products Developed

- A full-scale P4 preforming machine was designed, fabricated, installed and refined for the prototype production of pickup truck box preforms for the ACC's Focal Project II at the National Composites Center, Dayton, OH.

2.4 Technology Transfer Activities

2.4.1 Proprietary Reporting

- Numerous reviews with the ACC partners and their suppliers were held to discuss the progress and results of this project.
- Chavka, N.G. et al., "Carbon-Fiber Roving Development for the P4 Preforming Process," Automotive Composites Consortium Technical Report, TR P01-01, August 2001.

2.4.2 Non-Proprietary Publications and Proceedings

[1] Chavka, N.G. and Dahl, J.S., "P4 Preforming Technology: Development of High-Volume Manufacturing Methods for Fiber Preforms," ACCE/ESD: Advanced Composite Conference Proceedings, September 1998.

[2] Chavka, N.G. and Dahl, J.S., "P4: Glass Fiber Preforming Technology for Automotive Applications," Resin Transfer Molding, *SAMPE Monograph*, No. 3, May 1999.

[3] Chavka, N.G. and Dahl, J.S., "P4 Glass Fiber Preforming Technology for Automotive Applications," SAMPE Conference, Long Beach, CA, 1999.

[4] Chavka, N.G. and Dahl, J.S., "P4 Preforming Technology Development Utilizing E-Glass and Carbon Fibers," ACCE/DOE/ESD/SAMPE, Detroit, MI, 1999.

[5] Denton, D.L. et al., "Development of a Cost-Effective Manufacturing Process for a Composite Pickup Truck Box," SAMPE Detroit Conference, Detroit, MI, September 2000.

3. Deformation and Environmental-Induced Degradation of Structural Automotive Composites (ACC070)

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- Chrysler Corporation
- Ford Motor Company

Project Duration: January 1997 – December 1999

3.1 Executive Summary

The "Deformation and Environmental-Induced Degradation" Cooperative Agreement project (ACC070) developed a database, test procedures, and testing system to investigate the fundamental damage mechanisms in polymer-matrix composites as a function of specific, varied mechanical loading with concurrent environmental exposures. Inexpensive tensile creep fixtures were developed that allowed for accurate low-cost constant tensile creep evaluation of structural polymeric composites. The fixtures benefited original equipment manufacturers and thus the public by accurately measuring the effects of environmental durability sequences for material systems that were incorporated into current and future vehicles.

3.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

ACC070 was successful. The project plan was developed and implemented per the three-year program timing on budget.

Novel approaches were implemented by using compact creep fixtures that completed the work of standard dead-weight creep machines. The fixtures provide a significant cost savings when compared to dead-weight creep machines.

Accomplishments for the project were:

1. *Fabricate environment chamber*—Fabricated environmental chamber for investigation of materials in real-time environments. Chamber designed to allow up to 14 fixtures under test at one time.

2. *Establish baseline properties for polymeric composite material under evaluation*—Baseline tensile properties established for urethane/P4 directed fiber composite.

3. *Design compact tensile creep fixture that maintains at least 95% of original load on specimens*—Fixture design generated and computer-aided design drawings generated (Figure 3-1).

4. *Fabricate tensile creep fixture that maintains at least 95% of original load on tensile specimens*—First prototype fabricated and evaluation started. Results indicated spring constant variability outside of 95% load retention on tensile creep specimens.

5. *Design and fabricate second-generation fixture prototype and evaluate*—Fixture fabricated and evaluated. Results indicated spring constant variability within 95% load retention requirement. Only 3% reduction in load observed.

6. *Fabricate 14 creep fixtures for testing*—14 creep fixtures fabricated.

7. *Develop data acquisition (DAQ) system to monitor 14 fixtures at one time*—Labview

DAQ system assembled and placed into service.

8. *Develop motor driven loading equipment and specimen loading procedure*—A variable speed motor was modified to load fixtures at a constant rate of 0.04 (in/in)/min. The resulting motor allowed for outstanding control of creep fixture specimen loading accuracy.

9. *Creep test P4 urethane composite system at ambient and real-time environmental conditions*—Compare results to ORNL dead-weight creep machine raw data and creep models. Creep tested P4 structural composite material system at ambient and real-time environmental conditions. The 300 hour ambient distilled water-screening test was developed and implemented. Creep test results for 25% ultimate tensile strength (UTS) using seven fixtures immersed in distilled water indicated no significant variation from creep deformation models and raw data generated for test durations of 100, 300 and 600 hours. Fifty percent (50%) UTS data also compares very well.

10. *Develop and document tensile creep test fixture and procedure*—"Test Procedure to Measure Creep Deformation of Structural Polymer Composites Subjected to Environmental Exposure" published.

Figure 3-2 shows the creep fixture tensile creep data and how it compares to dead-weight machine tensile creep data from ORNL.

Problems Encountered:

The only problems encountered during the program were the failure of the first creep fixture prototype to maintain 95% of the initial load and the development of the software and DAQ system. Both issues were resolved within the time frame required to maintain the timing of the program.

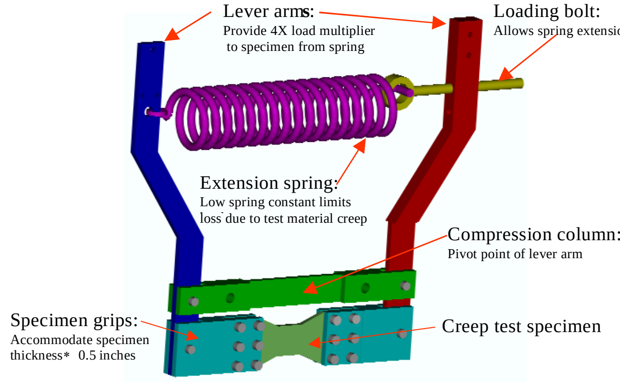

Figure 3-1. Tensile Creep Fixture

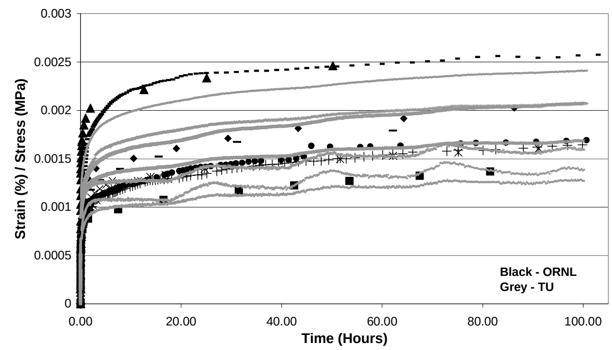

Figure 3-2. Comparison of Tensile Creep Data

3.3 Deliverables/Products Developed

- Stand alone executable control DAQ software to operate creep fixture experiments.
- Established tensile creep database.

3.4 Technology Transfer Activities

3.4.1 Proprietary Reporting

- U.S. Patent No. 5,79,463, "Self-Contained Constant Stress/Constant Strain Test Fixture," issued to ACC and the University of Tulsa on August 25, 1998.
- U.S. Patent Application No. 09/821,280 filed.

- Houston, D.Q. et al., "Test Procedure to Measure the Creep Deformation of Structural Polymer Composites Subjected to Environmental Exposure," ACC-TR-M-02-01.

3.4.2 Non-Proprietary Publications and Proceedings

[1] Meyer, L. et al., "The Effects of Stressed Environmental Exposure on the Durability of Automotive Composite Materials," *Polymers & Polymer Composites*, Vol. 7, No. 4, 1999.

[2] Luckey, S.G. et al., "The Creep Characterization of Structural Automotive Polymer Matrix Composites Using a Novel Fixture," Midwest Advanced Materials and Process Conference, Detroit, MI, September 12-14, 2000.

4. ACC Focal Project III: Composite Intensive Body Structure (ACC080)

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- Chrysler Corporation
- Oak Ridge National Lab (ORNL)
- Visteon
- University of Michigan
- University of Delaware
- National Composites Center

Project Duration: January 2002 – December 2006

4.1 Executive Summary

The goal of the ACC080 Focal Project III is to design, analyze and build a composite intensive body-in-white that matches the goals of PNGV, offering a minimum of 60% weight savings over steel at a cost close to steel, while meeting manufacturing, assembly, crash, and performance targets. It provides a focus for bringing together technology developed by each of the ACC working groups. This project will focus on carbon-fiber reinforced composites and the use of hybrid materials, faster manufacturing processes and design optimization including crash and rapid joining methods.

Focal Project III was divided into three key phases. Phase I was part of the previous Cooperative Agreement, and included the design development phase. In Phase I the project team completed the initial concept sketches, considered assembly methods, and narrowed down processing and material choices. A large amount of time was devoted to evaluating different contract houses to provide computer-aided design (CAD) and finite element analysis support. This selection was made in 1999 and in 2000 the math data for the concept was generated. The project identified the best design of a carbon composite body-in-white which matched the overall program objectives and maximized the mass reduction potential.

Phases II and III were part of this Cooperative Agreement funding beyond 2001.

- Phase II included the detailed design and build of one component to demonstrate high-volume processing methods. This included the design and build of the component as well as the needed assembly fixtures. The body component, a B-pillar, was successfully tested and correlated with the analytical predictions.
- Phase III included the detailed design and build of the complete body-in-white. However, due to both financial and personnel resources, the project was ended with the successful fabrication and testing of the carbon-fiber B-pillar as a demonstration.

4.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The goal of the ACC080 project was to guide, focus, and showcase the technology research of the four ACC working groups (Materials, Processing, Joining, and Energy Management). This project focused on carbon-fiber reinforced composites and the use of hybrid materials, faster manufacturing processes, design optimization including crashworthiness, and rapid joining methods.

At the conclusion of the previous Cooperative Agreement in December 2001, the team had:

- Completed Phase I of the program, including design optimization and finite element analysis of the selected body-in-white structure. The structure met or exceeded all design requirements.
- Identified critical manufacturing issues for Phase II of the project.
- Began work to build a learning tool, which will be a section of the body side to conduct further preforming and molding research. The tool incorporates challenging issues requiring developments such as preforming and molding variable thickness sections. The part obtained for the learning tool will also be used to address bonding issues.

The following accomplishments were achieved under the new Cooperative Agreement:

1. *Optimization of vehicle structure*—The first stage was to optimize the geometric structure to be efficient for composite materials. The philosophy was to produce a body-in-white with a low panel count, good connectivity, efficient load paths, stability and above all maximized section properties. New CAD data and finite element models based on initial concept sketches were generated from multiple concepts.

   Performance, cost, process ability and minimum thickness were key issues. The redesigned optimum structure is based on three sets of carbon materials: random chopped fibers for the majority of panels, stitched or woven material with core for the flat regular-shaped floor and roof structures, and either braided or helically wound lower rails.

2. *Assessment of load cases and optimization of material content*—From the sound platform of optimized geometry with efficient part integration the process of optimizing the material content against the prescribed load cases was undertaken. Topological and topographical optimization techniques were developed and utilized on the random material. The considerations for the sheet materials utilized ply management techniques for local patch and insert reinforcement. Commercially available simulation packages, Optistrut and Hyperopt, were used to optimize the structure.

   The load cases assessed were bending and torsion stiffness, that were exceeded by 80% and 200% respectively, and durability and abuse loads to ensure material fatigue allowables were met. The finite element model of the final concept for the body-in-white is shown in Figure 4-1.

3. *Evaluation of crash performance of structure*—Crash performance of the structure was developed with respect to two key criteria: controllable crush of the front rails and stability and integrity of the back-up safety structure. Non-linear crash analysis capability is not yet fully developed and therefore was not used for this study. High safety margins are placed on the back-up safety structure throughout the stable crush of the rails. The loads from the predicted crash pulse show that there is a factor of safety of three on material allowables.

   - The predicted mass of the complete structure is 86 kg, a 67% saving over the steel body-in-white mass and comfortably below the 60% target reduction (see Table 4-1).
   - The feasibility study undertaken demonstrates that the broad project objectives are feasible and the group continued with Phase II of the project.

4. *Development of Phase II*—Based on the design and analysis phase of the work, further materials and processing develop-

ments necessary for the demonstration part (Phase II of the project) were identified. The B-pillar, including sections of the roof rail and the rocker panel, was selected as a learning tool, to develop the processing and material technologies that would be needed to manufacture the body-in-white.

5. *Processing technology developments*—Being developed in conjunction with the ACC Materials and Processing Groups. These include:
    - High-volume processes for part fabrication and assembly
    - Expansion of P4 processes for carbon
    - Evaluation of other processes as needed
    - Identification of methods to reduce molding time
    - Adhesive bonding
- Material property characterization of carbon-reinforced composites

6. The Materials and Processing Groups have developed the P4 process for carbon fiber. Molding of the B-pillar was also developed using an injection-compression methodology for Structural Reaction Injection Molding (SRIM). Flow simulation of the SRIM process using our preforms aided in the process development. The challenges for the performing and molding development included the high-fiber loading and the variation in the thickness of the part and wall geometries needed for the mass optimization, as well as the management of the carbon-fiber strand, which behaves very differently from glass fiber.

7. The inner and outer B-pillars were successfully molded. Joining was achieved via adhesive bonding, using a heated fixture and an advanced epoxy adhesive.

8. The structures were analyzed for fiber content and material properties, and this information was used in structural models to predict the bending and torsional strength of the components. Mechanical bending and torsional tests were carried out, and found to compare well with the analytical predictions.

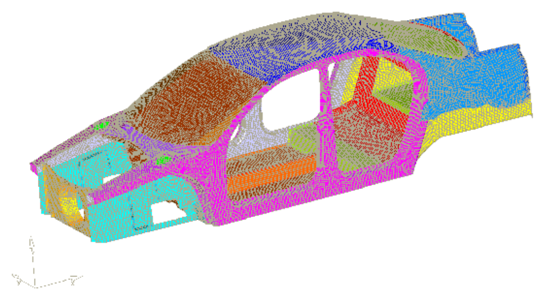

Figure 4-1. Body-in-White Finite Element Model

Table 4-1. Mass Distribution of Materials in Body-in-White

Materials	Mass (kg)
Chopped Carbon Material	54.83
Woven Carbon Fabric Material	17.73
Core Material	3.21
Adhesive	1.58
Analyzed Aluminum Inserts	6.41
Additional Inserts	2.39
Total	86.15

4.2.1 Computer Modeling Work

Computer modeling work under this project is reported in the previous section.

4.3 Deliverables/Products Developed

- Design optimization and finite element analysis of the selected body-in-white structure. The structure met or exceeded all design requirements.
- P4 preforming technology for carbon fibers was developed, including the variation in wall thickness needed for mass optimization and the effect of carbon

strand geometry on the preform uniformity.

- SRIM molding technology for carbon-fiber performs was developed. This was enhanced by flow simulations of the injection-compression SRIM process.
- High-rate adhesive bonding technology allowing the structure to be assembled in a time acceptable in automotive production was achieved.
- Structural testing of the assembly showed values consistent with those needed for the body-in-white, and closely matched by analytical predictions.

4.4 Technology Transfer Activities

4.4.1 Proprietary Reporting

- Numerous reviews with the ACC partners and their suppliers were held to discuss the progress and results of this project.

4.4.2 Non-Proprietary Publications and Proceedings

[1] Boeman, R. and Johnson, N., "Development of a Cost Competitive, Composite Intensive, Body-in-White," SAE-2002-01-1905, Future Care Congress, Arlington, VA, June 3, 2002.

[2] Iobst, S.A. et al., "The Automotive Composites Consortium B-Pillar Molding Program," Society of Plastic Engineers Automotive Composite Conference, Troy, MI, September 12, 2005.

[3] Iobst, S.A. et al., "Fabrication of the Automotive Composites Consortium Carbon-Fiber B-Pillar," Society for the Advancement of Materials and Process Engineering, Baltimore, MD, June 3, 2007.

[4] Dahl, J. et al., "The Influence of Fiber Tow Size on the Performance of Chopped Carbon-Fiber Reinforced Composites," Society for the Advancement of Materials and Process Engineering, Seattle, WA, November 2005.

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5. Predictive Technology Development & Composite Crash Energy Management (ACC100)

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- Michigan State University
- U.C. Santa Barbara
- Stanford University
- Rutgers University
- University of Utah
- Virginia Polytechnic Institute
- South Dakota School of Mines & Tech.
- University of Cambridge-UK
- University of Nottingham-UK
- Imperial College-UK
- Oak Ridge National Laboratory
- Lawrence Livermore National Laboratory
- National Composites Center
- Visteon
- Zoltec
- Fortafil
- Hexcel
- Ashland
- A&P Technologies
- Excel Pattern Works
- Delsen Testing Labs

Project Duration: February 1995 – Present

5.1 Executive Summary

Automotive (polymeric) composite structures offer the potential for advantages in mass savings, durability, NVH (noise, vibration and harshness), design flexibility, and meeting or exceeding crash-performance requirements and standards.

The project's mission is to provide the U.S. Automotive Industry with a global technological advantage by developing state-of-the-art knowledge and engineering design and analysis tools necessary to demonstrate, manufacture and deploy composite lightweight vehicle technologies for structures and systems that meet and/or exceed performance, functional and safety requirements.

The project's goal is to develop the understanding of the mechanical behavior of composites that is necessary to develop the tools and methodologies needed to analyze and predict the crash-energy management characteristics and response of automotive structural components.

The project's objectives and approach include:

- Conducting experimental tests to characterize the quasi-static and dynamic properties (including coupled properties of selected structural composite materials, damage modes, and progression mechanisms.
- Developing models based on phenomenological as well as advanced novel micro-mechanical approaches to predict the material and structural responses during the regimes of mechanical behavior.
- Verifying and validating the computational tools by predicting quasi-static and dynamic behavior of experimental tests at the coupon and component levels.

5.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

This project has been focused on delivering the necessary fundamental knowledge and tools including efficient computational modeling methodologies that are robust, physics-based, and predictive far exceeding the current state-of-the-art commercial computer-aided engineering (CAE) tools that are mostly simulation-driven (not-fully-predictive). One of the benefits will be the overcoming of one of the major bottle-necks (lack of robust predictive models) to volume-production and deployment of automotive structural composites.

Extensive laboratory tests have been conducted to characterize the effects of materials, architecture and loading conditions on mechanical behavior. The analytical prediction of the quasi-static and dynamic/crash performance of composite structures, however, remains under intensive research and development. Due to the topic's multi-faceted complexities, several programs have been executed in this project during the Cooperative Agreement period to develop the analytical capabilities. Although significant additional work remains before complete sets of tools and methodologies are available for the full-response analysis of the crash behavior of polymer composite structures, the project has been able to successfully expose and address some of the major underlying concepts that are basic yet unique to these very complex material systems (Figure 5-1).

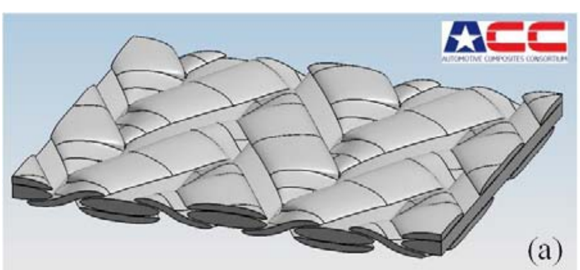

Figure 5-1. 3D Computer Model of Carbon-Braided Textile System

The overall project is divided up into five general tasks:

Task 1—Characterize composites' properties and their constituents within a hierarchical framework (manufacturing, lifecycle) for automotive applications.

Task 2—Characterize the dominant micro-, meso- and macro-mechanical mechanisms responsible for damage initiation, progression and energy absorption.

Task 3—Characterize the coupled material-structural behavior of composites in order to direct the development of new and improved material systems and models.

Task 4—Develop, verify and validate efficient and robust modeling and analysis tools for the prediction of damage initiation, progression, energy absorption and overall crash behavior of composite components in lightweight vehicle structures using micro-mechanical, phenomenological or hybrid approaches.

Task 5—Develop design, testing, modeling and analysis recommendations for automotive composites applications in vehicle development.

Project Status:

- Mechanical characteristics of various fiber-reinforced composites (e.g. glass/carbon, random/textiles) were investigated quailtatively and quantitatively, and several of the primary controlling damage parameters were identified using state-of-the-art methodologies.
- Newly exposed challenging factors which influence strength, post-strength and energy absorption have been studied (experimentally/computationally) in order to yield robust understanding of crush (Figures 5-2 and 5-3).
- Novel state-of-the-art databases (modeling and materials) have been under

development and are nearing their last phases. These databases are not all-encompassing and are limited to the specific materials tested and unique methodologies developed.

- Several computational strategies and tools have been formulated and developed which incorporate novel physics-based modeling concepts (Figures 5-2 and 5-3). Due to the complexity of the predictive modeling methodologies, this work is still ongoing and will likely continue for the foreseeable future.

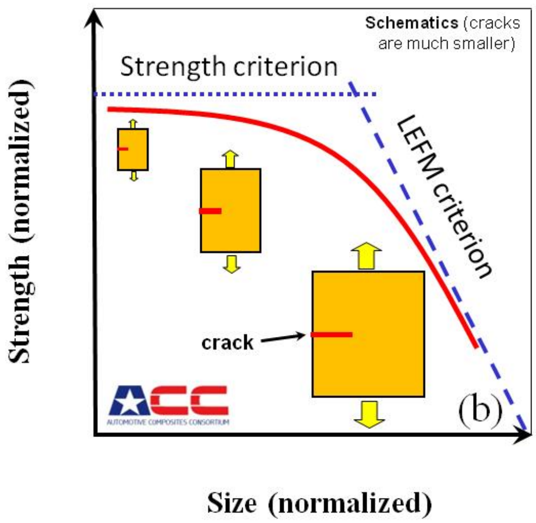

Figure 5-2. Size-Effects Studies – Qualitative Schematic Showing Effect of Specimen/ Structure Relative Size on its Strength Characteristics

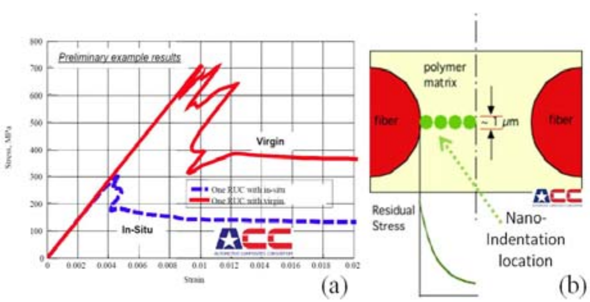

Figure 5-3 In-Situ Property Studies: (a) Example Showing Some of the Potential Effects of Manufacturing/Processing on the Mechanical Response of a Materials Sample; (b) Local Effects and Variations of Properties

5.2.1 Computer Modeling Work

See Task 3 through Task 5 outlined above.

5.3 Deliverables/Products Developed

- Qualitatively and quantitatively understanding of the underlying mechanical principles and physics of energy absorption in composites.
- Modeling methodologies and computational algorithms necessary to incorporate within robust predictive tools.
- Materials testing and experimental data (database).
- Modeling algorithms and computational procedures (database).
- General testing, modeling and analysis recommendations and guidelines for automotive composites applications.

5.4 Technology Transfer Activities

5.4.1 Proprietary Reporting

- Numerous reviews with the ACC partners and their suppliers were held to discuss the progress and results of this project.

5.4.2 Non-Proprietary Publications and Proceedings

Selection out of more than 70 publications:

[1] Caner, F.C. et al., "Microplane Model for Fracturing Damage of Triaxially Braided Fiber-Polymer Composites," *Journal of Engineering Materials and Technology*, Vol. 122, (2), 2011.

[2] Smilauer, V. et al., "Multiscale Simulation of Fracture of Braided Composites via Repetitive Unit Cells," *Engineering Fracture Mechanics*, Vol. 78, (6), pp. 901-918, 2011.

[3] Shahwan, K.W., "Thinking Out of the Metallic Box," ACC Activities & Challenges, 2008 Plastic and Composite Intensive Vehicle (PCIV) Safety Workshop, US-DOT/RITA Volpe Center, Cambridge, MA, August 4, 2008, (http://www.volpe.dot.gov/safety/pciv/docs/shahwan.pdf)

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[5] Song, S. et al., "Effects of Matrix Microcracking on the Response of 2D Braided Textile Composites Subjected to Compression Loads," *Journal of Composite Materials*, Vol. 44 (2), pp. 221-240, 2009.

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[7] Song, S. et al., "Compression Response of 2D Braided Textile Composites: Single Cell and Multiple Cell Micromechanics Based Strength Predictions," *Journal of Composite Materials*, Vol. 42, (23), pp. 2461-2482, 2008.

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[11] Xie, D. et al., "Fracture Criterion for Kinking Cracks in a Tri-Material Adhesively Bonded Joint Under Mixed Mode Loading," *Engineering Fracture Mechanics*, Vol. 72, pp. 2487-2504, 2005.

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[14] Quek, S.C. et al., "Compressive Response and Failure of Braided Textile Composites: Part 2 – Computations," *International Journal of Non-Linear Mechanics*, Vol. 39, pp. 649-663, 2004.

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[16] Song, S. et al., "Post-Peak Response of Braided Textile Composites Under Compressive Loads," 21st American Society for Composites (ASC) Annual Technical Conference, Dearborn, MI, 2006.

[17] Van Otten, A.L. et al., "Evaluation of Sandwich Composites for Automotive Applications," 20th American Society for Composites (ASC) Annual Technical Conference, Philadelphia, PA, 2005.

[18] Van Otten, A.L. et al., "Evaluation of Sandwich Composites for Automotive Applications," SAMPE Conference, Long Beach, CA, 2004.

[19] Waas, A.M. et al., "Microstructural Instabilities in Braided Textile Composites," ASCE Engineering Mechanics Conference, Seattle, WA, 2003.

[20] Quek, S.C. et al., "Failure Mechanics of Triaxially Braided Carbon Composites Under Combined Bending-Compression Loading," 18th American Society for Composites (ASC) Annual Technical Conference, Gainesville, FL, 2003.

[21] Quek, S.C. et al., "Instabilities of Braided Textile Composites Under Uniaxial Compressive and Biaxial Loadings," 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Denver, CO, April 22-25, 2002.

[22] Quek, S.C. et al., "Damage Mechanisms of Carbon Fiber Braided Textile Composite Laminates," ASME Summer Meeting, San Diego, CA, 2001.

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[27] Xie, D. et al., "Discrete Cohesive Zone Model to Simulate Static Fracture in Carbon Fiber Composites," 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin TX, (AIAA-2009-2320), April 18-21, 2005.

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[30] Warrior, N.A. et al., "Effects of Fiber Architecture on the Energy Absorption of Damaged Thin-Walled Composite Tubes," 18th Annual Technical Conference, American Society for Composites, University of Florida, Gainesville, FL, October 19-22, 2003.

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[34] Salvi, A. et al., "Shear Strain Rate Dependency in Polymer Matrix Composites," 6th International Conference of Deformation, Yield, and Fracture of Composites at UMIST, Manchester, UK, April 4-5, 2001.

[35] Han, X. et al., "Dynamic Infrared Imaging of Crush Tests of Composite Tubes," QNDE Conference, Montreal, Canada, July 25-30, 1999.

[36] Caliskan, A. et al., "Static and Dynamic Crush of Composite Tubes," ASME Mechanics & Materials Conference, Session on Recent Developments in the Study of Impact of Composite Materials, Blacksburg, VA, June 28-30, 1999.

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6. Creep, Creep Rupture and Environment-Induced Degradation of Carbon and Glass-Reinforced Automotive Composites (ACC105)

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- DaimlerChrysler Corporation
- University of Tulsa
- Bayer
- Oak Ridge National Lab (ORNL)

Project Duration: January 2000 – December 2001

6.1 Executive Summary

Time-dependent properties of structural automotive composites have been identified as among the most critical areas of concern within the automotive industry. Properties such as creep and creep rupture are not only design-critical, but are also expensive and time-consuming to measure in the laboratory. The "Creep, Creep Rupture and Environment-Induced Degradation of Carbon and Glass-Reinforced Automotive Composites" Cooperative Agreement project (ACC105) developed a database, test procedures, testing system and test methodology to investigate the fundamental damage mechanisms in polymer-matrix composites as a function of specific, varied mechanical loading with concurrent environmental exposures including the ability to understand a material response to creep rupture. Relatively inexpensive tensile creep, creep rupture fixtures were developed that allowed for accurate time dependent evaluation of structural polymeric composites. The fixtures benefited original equipment manufacturers and thus the public by accurately measuring the effects of environmental durability sequences for material systems that were incorporated into current and future vehicles.

6.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project plan was designed, developed, fabricated and implemented per the three-year program timing on budget. An inexpensive creep rupture fixture was developed that allowed for accurate evaluations of structural polymeric composites up to the point of rupture.

Conclusions of the program can be summarized by reviewing Figure 6-1 and Table 6-1 which show the final creep rupture fixture and creep rupture fixture targets and actual data achieved. Creep, creep rupture test results shown in Figure 6-2 indicate an excellent correlation between the creep rupture fixture data and ORNL data.

Novel approaches were implemented by using the compact creep rupture fixture that completed the work of standard dead-weight creep machines.

1. *Establish baseline properties for polymeric composite material under evaluation*—Baseline tensile properties established for urethane/P4 directed glass and carbon fiber, carbon and glass mats and carbon-fiber prepreg.

2. *Design and document compact inexpensive creep rupture fixture that is capable of testing high performance carbon and glass reinforced composites*—Developed design that allows easy conversion of current compact creep fixture into creep rupture apparatus. Fixture can generate a load multiplication of at least 180:1, which can apply up to 5,650 lbs. of load on the test specimen. Fixture geometric envelope was

500mm x 250mm x 500mm. Computer-aided design drawings generated.

3. *Fabricate 1st generation creep, creep rupture fixture from design*—1st generation creep, creep rupture fixture fabricated.

4. *Evaluate creep, creep rupture capability of 1st generation fixture*— Fixture evaluated, results indicated that high compressive forces on the threaded rod made loading the test specimen extremely difficult.

5. *Improve loading apparatus for 1st generation fixture*—A small steel ball was placed on the right end of the threaded rod and an adjustable thrust bearing was installed on the lever arm. This resulted in much smoother and easier loading and unloading of the specimen.

6. *Design and fabricate 2nd generation fixture*—2nd generation fixture and load multiplier fabricated.

7. *Evaluate creep, creep rupture capability of 2nd generation fixture*—2nd generation fixture and load multiplier evaluated. Results indicated a problem with the pulley system for the multiplier assembly. The attachment to the pulley was investigated and was determined that the friction generated by the pulley cables was too high.

8. *Design and fabricate 3rd generation fixture*—3rd generation fixture fabricated. The following improvements were implemented. Two pulleys, two sprockets and an improved lever arm assembly were added. A clutch was added to adjust the weight height during a test without perturbing the specimen. A loading procedure modification to obtain the desired loading rate was added. The 3rd generation creep, creep rupture fixture is shown in Figure 6-1. Table 6-1 indicates the creep rupture fixture targets and the actual values achieved by the fixture.

9. *Implement data acquisition (DAQ) system to capture strain, temperature and humidity data during evaluation*—DAQ assembled with Labview software enabled real-time creep, creep rupture data including strain, temperature and load data to be measured simultaneously. DAQ system improvements included installing an Ethernet card to enable real-time data transfer to office PC for analysis of creep, creep rupture data.

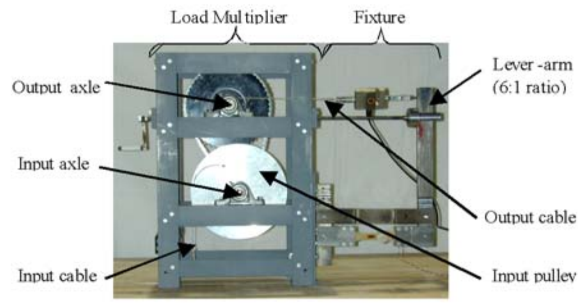

Figure 6-1. Creep Rupture Test Set-Up

Table 6-1. Creep Rupture Test Results

	Target	Actual
Maximum Load Capacity	2562 kg	2472 kg
Load Ratio	At last 180:1	187:1
Geometric Envelope	500mm x 250mm x 500mm	572mm x 191mm x 687mm
Weight	35 kg	32 kg
Fixture Conversion	To a spring-loaded in-situ creep fixture	Ability to make the conversion
Maintenance of Initial Load	≥95%	P4 material: 96.5% on average

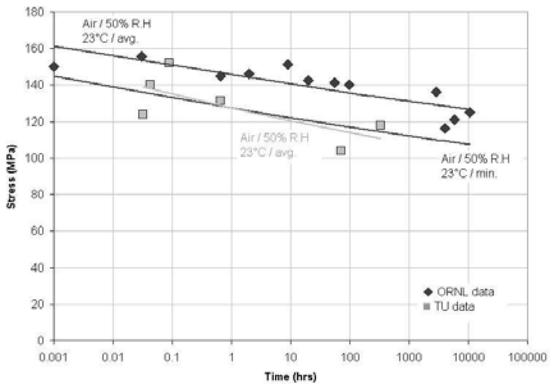

Figure 6-2. Creep, Creep Rupture Test Results

10. *Compare creep, creep rupture results to ORNL creep rupture data*—Creep, creep rupture test results shown in Figure 6-2 indicate an excellent correlation between the creep rupture fixture data and ORNL data.

<u>Problems Encountered</u>:

Problems encountered during the program indicated high compressive forces on the threaded rod encountered in the 1st generation creep rupture fixture. A problem with the pulley system for the multiplier assembly on the 2nd generation fixture resulted in high friction. All issues were resolved within the time frame required to maintain the timing of the program.

6.3 Deliverables/Products Developed

- Labview DAQ assembled and placed into service.
- Creep rupture fixture fabricated.
- Improvements made to the variable speed motor to load fixtures at a constant rate of 0.02 (in/in)/min.

6.4 Technology Transfer Activities

6.4.1 Proprietary Reporting

- Stand alone executable control DAQ software to operate creep fixture experiments.
- Established tensile creep database.
- Lombart, V. et al., "A Novel Creep Rupture Fixture for Testing Automotive Composite Materials: A Final Report," <u>Materials Work Group Report</u>, TR-M03-02.

6.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

7. A Novel Fixture for Compression Testing of Composites (ACC205)

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Project Duration: January 2002 – December 2005

7.1 Executive Summary

Compression properties of fiber-reinforced composites are often inferior to the tension properties of the same materials. Accurate measurement of the compression behavior of composites is thus important. Traditional compression fixtures for composites are large, heavy, expensive, and require the use of a load frame. This report describes a novel compression fixture for composites that overcomes these shortcomings of traditional fixtures. The fixture described herein reverses an external tensile load to apply compression to a standard composite compression specimen. Because it is light, compact, and loaded in tension, the fixture is amenable to in-situ type testing using spring loaded fixtures as well as creep compression testing on dead-weight tensile creep machines. This report describes the design, development, and prove-out testing of this novel compression fixture.

7.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

This research was motivated by the need for the accurate yet inexpensive, simple, and versatile compression testing of composites – in particular in the automotive industry.

A composites compression testing fixture was desired that would achieve the following goals. First, the fixture needed to be externally loaded in tension so that the fixture could be used with in-situ spring-loaded devices as well as standard dead-weight tensile creep machines. The fixture needed to efficiently (at least 95%) convert the external tensile load into compression on the test specimen. The fixture needed to apply true compression, such that the difference in strain from one side to the other of an isotropic test specimen was less than 5%. In addition, the fixture needed to be compact, lightweight, low-cost, durable, and easy-to-use.

1. *Design, fabricate and test prototype composite compression fixtures*—Several generations of prototypes were designed, fabricated, and tested before the final design, was created. The final design overcame the shortcomings of the earlier models and was deemed worthy of further development.

   The fixture utilizes four loading rods that pass through two compression block assemblies (Figure 7-1). The compression test specimen is captured between the two compression blocks (Figure 7-2) and loaded through two pairs of wedge-shaped grips. Each loading rod passes through both compression blocks, sliding through the first compression block and then rigidly fastening to the second block. When the four rods are loaded in tension, the two compression blocks are thus pulled closer together, and the specimen goes into compression.

   The new compression fixture efficiently converts an external tensile load to a uniform state of compression on a composite specimen of standard dimensions.

2. *Prove-out testing*—The new compression fixture was subjected to a series of tests designed to prove that the fixture met the objectives outlined.

   This test showed several positive results. First, there is a negligible loss in transmission of load from the load frame (tension) through the fixture to the specimen (compression), and second, the fixture shows no variation in performance from one loading cycle to the next.

   The results of these and other tests performed on load frames were encouraging, and led to the conclusion that the new compression fixture performed its basic function: efficiently converting an external tensile load to a state of uniform compression on a test specimen.

   Subsequent prove-out tests were performed to confirm the versatility of the new fixture. In particular, the new compression fixture was tested in conjunction with a patented in-situ spring loaded test fixture developed in previous research. The new compression fixture adapts quite well to the in-situ spring-loaded fixture.

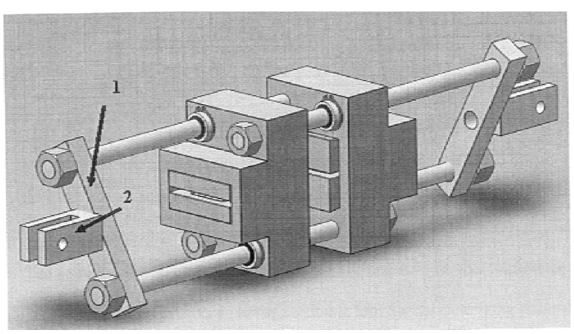

Figure 7-1. Solid Model of the Compression Fixture with Labels Showing Main Components

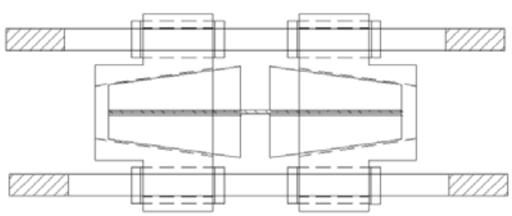

Figure 7-2. Side View Drawing of Fixture Showing Position of Compression Specimen

   The final phase of prove-out testing involved testing several typical automotive composites using the new fixture.

   Problems Encountered:

   Thorough testing of the new fixture has revealed some limitations to its use. The most restrictive of these is the maximum load, which is currently about 16 kN. This results in a maximum compressive stress on a standard specimen (3mm x 25mm cross-section) of about 200 MPa. Increasing the size of the load coupler (shown in Figure 7-1) would increase the load capacity of the fixture, since this is the most highly-stressed component in the current design.

   Development testing on the new fixture also revealed that it is critical that all parts be accurately machined and within tolerances. Small dimensional deviations can easily result in unacceptably high bending strains on the compression specimen. (This phenomenon, while real, is part of the challenge inherent to compression testing and is certainly not limited to the new fixture.)

7.3 Deliverables/Products Developed

- Compression Fixture Developed and Fabricated. Several copies of the final prototype fixture were subsequently fabricated.
- Accurate compression data generated.
- Procedure developed to conduct accurate compression evaluation of composite material systems.

7.4 Technology Transfer Activities

7.4.1 Proprietary Reporting

- Presentations at ACC and USAMP Offsites.

7.4.2 Non-Proprietary Publications and Proceedings

[1] Luckey, S. et al., "The Creep Characterization of Structural Automotive Polymer Matrix Composites Using a Novel Fixture," SAMPE (Society for the Advancement of Materials and Process Engineering) Conference Proceedings, Dearborn, MI, September, 2000.

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8. Advanced Materials and Processing of Composites for High-Volume Applications (ACC932)

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- Chrysler Corporation
- Ford Motor Company

Project Duration: March 2008 – Present

8.1 Executive Summary

Develop a low-cost carbon-fiber reinforced sheet molding compound (SMC) with mechanical properties and processing characteristics superior to current commercial materials. Investigate BLRT to enable implementation of minimum thickness composite closure panels to eliminate weight added for appearance. Explore automotive molding processes including Long Fiber Injection (LFI), Direct Long Fiber Thermoplastic (DLFT), and co-mingled thermoplastic materials.

8.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

1. *Develop a low-cost carbon-fiber reinforced SMC with mechanical properties and processing characteristics superior to current commercial materials—*

Properties and property consistency:

- Tensile Modulus 35-40 Gpa.
- Tensile Strength 200-250 MPa.
- Coefficient of variation < 10%.

Compounding and molding processes – Minimal deviation from existing glass reinforced SMC. Molding cycle time < 3 minutes at 1.5mm thickness.

Partner with Tier-1 automotive SMC supplier to take advantage of existing compounding and molding capabilities and to ensure rapid implementation of developed technology. Focus on using lower cost carbon fibers. Initial development aimed at a structural material, then explore an appearance Class-A grade material.

2. *Investigate BLRT to enable implementation of minimum thickness composite closure panels to eliminate weight added for appearance—*

Develop a validated finite element model that can predict the severity of BLRT distortions based on part design to allow original equipment manufacturers to use minimum thickness panels while still meeting customer expectations for surface appearance.

BLRT project to be completed by December 2010. Seventy-five percent (75%) of experimentals designed to establish the relationship between material and process factors are completed. Preliminary finite element molding over predicted the severity of BLRT induced distortions. More realistic material models are being created to improve the correlation between experiments and model prediction.

3. *Explore automotive molding processes including long fiber injection (LFI), direct long fiber thermoplastic (DLFT), and co-mingled thermoplastic materials—*

Process nylon thermoplastic resin in LFI and DLFT processes. Determine processing parameters, establish composite material properties, and gain understanding of potential automotive applications.

Complete upgrade of injection molding tool for future processing trials. Work with thermoplastic consulting expert to establish thermoplastic formulations. Establish molding facility for DLFT processing studies. Process and characterize nylon composite formulations.

8.3 Deliverables/Products Developed

- Develop a low-cost carbon-fiber reinforced SMC with mechanical properties and processing characteristics superior to current commercial materials.

8.4 Technology Transfer Activities

8.4.1 Proprietary Reporting

- Presentation at ACC and USAMP Offsite.

8.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

1. Structural Cast Magnesium Development (AMD111 & AMD112)

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- Advanced Magnesium Technologies North America
- American Foundry Society
- CANMET-Materials Technology Laboratory
- Creative Concepts Company Inc.
- DaimlerChrysler Corporation
- Dead Sea Magnesium Inc.
- Eck Industries, Inc.
- EKK Inc.
- Flow Science Inc.
- Ford Motor Company
- General Motors Corporation
- Georgia Institute of Technology
- Gibbs Die Casting Corporation
- Hayes-Lemmerz International Inc.
- Hetke consulting LLC
- Henkel Surface Technologies
- Hydro Magnesium
- Intermet Corporation
- Lawrence Livermore National Laboratory
- LightWeightStrategies LLC
- Lunt Manufacturing Company Inc.
- Manufacturing Development & Service Inc.
- Meridian Technologies Inc.
- Mississippi State University
- Noranda Magnesium Inc.
- Oak Ridge National Laboratory
- Reid and Associates LLC
- Ryobi Die Casting USA Inc.
- Sandia National Laboratory
- Techanalysis Inc.
- Thixomat Inc.
- University of Windsor
- UES Inc.
- U.S. Department of Energy
- Westmoreland Mechanical Testing and Research Inc.

Project Duration: January 2001 – August 2006

1.1 Executive Summary

The *"Structural Cast Magnesium Development" (SCMD)* project focused on:

1. Resolving critical issues that presently limited the large-scale application of magnesium castings as automotive structural components.
2. Supporting the relationship with the *FreedomCAR and Fuel Partnership Plan* to: "Enable the high volume of vehicles that were half the mass, recyclable, match or surpass quality and durability versus today's vehicles."

The SCMD project activities included the development of both the science and technology necessary to convert an existing aluminum front engine cradle to a structurally designed magnesium front-engine cradle as shown in Figure 1-1. The redesign of this cradle involved all of the difficult manufacturing issues including: the investigation of all casting processes; techniques to join dissimilar metals; solving harsh service environment challenges including corrosion, fatigue and load retention of fasteners. This project also required the investigation, development and testing of new magnesium alloys to meet these requirements.

In addition, the SCMD Project team had to design the magnesium cradle to the exact tolerances of the existing aluminum cradle that was currently in production by General Motor's

Corvette Team. Existing production practices would not be changed for the magnesium cradle. This included the use of existing sub-frame supports, steel fasteners, nut-runners, and assembly techniques already in use. Also, the existing attachment points and engine compartment clearances of the aluminum cradle would not be changed. Most important, all phases of the project's investigative programs had to be successfully completed on time and economically priced to meet Job #1 for the 2006 Corvette Z06.

1.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The SCMD project approach to achieve these major accomplishments (within a short period of time), required the cooperation of the original equipment manufacturer members, industry and the scientific support teams, all working with the GM Corvette Team to solve the design, material and process issues. The key activities of this investigation are listed below.

- Improve the scientific understanding of magnesium alloys.
- Develop a cost model that compared cast magnesium 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.
- Complete all of the scientific project tasks relevant to microstructure-property modeling, corrosion mitigation, joining behavior and non-destructive evaluation methods etc.
- Convert an existing aluminum cradle to magnesium and have the parts ready for testing, and approved for 2006 Corvette Z06's Job #1. Both industry and the scientific development part of this project worked simultaneously to solve all aspects to meet the time schedule.
- Transfer the knowledge to industry and identify the lessons learned by this project.

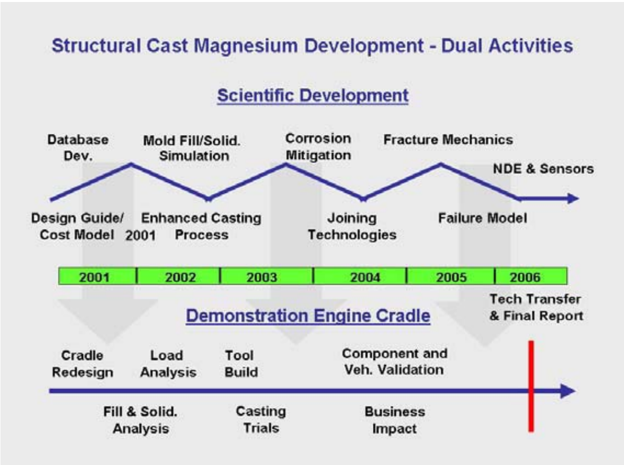

Figure 1-1. Dual-Project Path for Science and Magnesium Demonstration Casting Validation Activities

<u>Conclusions</u>:

The aluminum cradle was successfully redesigned to magnesium and process improvements were made to the existing high-pressure die-casting processes. Approximately 150 magnesium prototype engine cradle castings (Figures 1-2 and 1-3) were provided to SCMD project participants by Year End 2003 to start the intensified material property investigations, non-destructive evaluations, database investigations and all of the bench and vehicular testing programs. Results from all of these investigations and additional samples of magnesium alloy parts (AE44, AM50A, AM50, and AM60) were forwarded to: CANMET, Georgia Institute of Technology, Lawrence Livermore National Laboratory, and Westmoreland Mechanical Testing and Research, Inc. for additional testing. The results are included in the database file. In addition, the same information was sent to Mississippi State University to be used for the investigation and development of the predictive failure model.

Based on the success of the ongoing tests, the GM Corvette Team initiated a separate and parallel investigation to evaluate the use of the magnesium cradle in the 2006 Corvette Z06 production vehicle, while the total magnesium testing and evaluation program for the SCMD project proceeded. All of the above evaluation tests (including bench and vehicular) were satisfactory, and with that information, the use of a magnesium cradle was designated for Job #1 by the Corvette Team.

1.2.1 Computer Modeling Work

The modeling techniques for the SCMD project were generally identical to the Design and Product Optimization for Cast Light Metals project (LMD110), but related exclusively to magnesium alloys. A synergistic program that included experiments, micromechanical finite element modeling of local microstructures, and macroscale modeling of the microstructure-property relations of fatigue will provide definite results for optimizing the design of structural cast components. Relations were developed that contain explicit treatment of each inclusion type in order to offer a link between quantitative characterization of inclusion populations and fatigue life estimates, including the variability of fatigue life. Such relations provide a link in foundries to help guide the selection of section thickness, impurity and gas level controls, solidification which are ongoing for the various types of magnesium alloys.

Figure 1-2. Prototype Castings

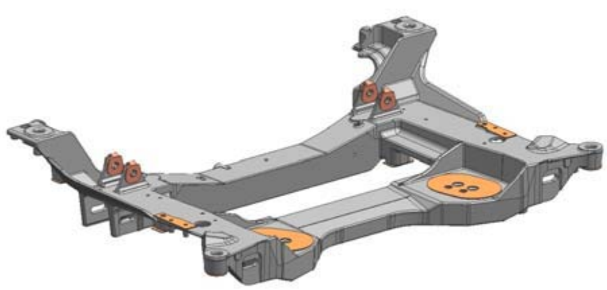

Figure 1-3. Machined Magnesium Cradle

Problems Encountered:

The original dates indicated in the project's Statement of Work (CRADA) were not initially met because of delays in the approval of: (a) purchase orders for collaborative work with CANMET; (b) the development of a new generic work agreement and (c) miscellaneous delays in approving CRADA and cooperative documents. Consequently, the project was extended one year, to be completed in 2006. This problem was reported in the yearly report submitted to the USAMP-AMD. All project participants fully cooperated to make up for this lost time.

1.3 Deliverables/Products Developed

- An aluminum and magnesium database was started in 1995 with the project, Design and Product Optimization for Cast Light Metals, and a copy of the first database was included in that Final Report published on October 31, 2001. The same database was expanded for the two current magnesium projects: Structural Cast Magnesium Development (SCMD) and the Magnesium Powertrain Cast Component (MPCC).

1.4 Technology Transfer Activities

An impressive list of both proprietary and non-proprietary publications resulted from the SCMD project.

1.4.1 Proprietary Reporting

- USAMP and DOE Reports and briefings at Offsites.

1.4.2 Non-Proprietary Publications and Proceedings

[1] Winner of the North American Die Casting Association, 2006 International Die Casting Competition for Best Magnesium Casting over 0.5 lbs.

[2] Winner of the International Magnesium Association Award for Excellence, for Best Application of Magnesium in 2005.

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[4] Lee, S. G. et al., "Macro-Segregation in High-Pressure Die-CastAM60B Alloy," Magnesium Technology 2005 Symposium, The Minerals, Metals & Materials Society (TMS) Annual Meeting, San Francisco, CA, February 14-17, 2005.

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2. Low-Cost Powder Metallurgy for Particle-Reinforced Aluminum Composites (AMD210 & AMD220)

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- General Motors Corporation
- DaimlerChrysler Corporation
- Hoeganaes
- MatSys
- Metaldyne
- MET Group
- Stackpole
- North-St. Gobain Industrial Ceramics
- Valimet
- Ames Lab Iowa State University
- Oak Ridge National Lab (ORNL)
- NIST
- Arizona State University
- University of Michigan
- Aluminum Consultants Group
- Saint-Gobain Ceramic
- Technologies Research Corporation

Project Duration: April 1997 – May 2004

2.1 Executive Summary

The purpose of the USAMP AMD210 and AMD220 collaborative projects was to develop low-cost metal matrix composite components from powder metallurgy (PM) processes, and enable the commercialization of two promising new particle-reinforced aluminum (PRA) composite technologies for net-shape forming of selected automotive powertrain components. The demonstration parts selected for this work were a connecting rod (used in Direct Powder Forging, DPF) for high-strength/high-temperature applications, and a pair of dual cycloidal crescent automatic transmission pump gears (used in Press and Sinter, PS) for moderate strength applications. During this seven-year project (1997-2002), through participation by leading suppliers, the PMPRA Consortium established (and enhanced) technical and manufacturing capabilities in North America to provide low-cost PMPRA components to the automotive industry. This work was aimed at replacing current ferrous parts with lighter-weight components to save vehicle weight and improve efficiency and fuel economy. PRA machining technology and PRA composite design/modeling methodologies were also identified and pursued for advancement in this USAMP collaborative project so as to develop comprehensive supply base capabilities for design and manufacture of PRA automotive components. Both, the PS and DPF manufacturing methods have been developed with a vertically integrated team of original equipment manufacturers (OEMs), material and product suppliers, national laboratories and academia. The developed candidate components were delivered as prototypes for OEM evaluation and testing.

2.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Through participation by leading suppliers, the project team sought to establish (and enhance) technical and manufacturing capabilities in North America to provide low-cost PMPRA components to the automotive industry through the USAMP partners.

The “Press and Sinter” (PS) program focused on enhancement of component durability (wear resistance) by process optimization and coating development. Design, fabrication and industrial trials of new compacting and coining dies were completed. The die dimensions were modeled taking into account dimensional changes during processing, and the necessity to accommodate a variety of coating thickness. Close to300 Dual Cycloidal Crescent (DCC) aluminum-silicon PM alloy gear-sets for the 4T80 pump were fabricated. Gear dimensions and concentricity were improved significantly and met specifications. Materials characteristics of the developed aluminum-silicon PM alloys (PS alloys) met required limits of mechanical properties. PS alloy gears exhibited hardness up to 68-75HRB. Crush tests of sintered and coined gears performed at the AGD and PCD plants of Stackpole Limited showed that outer gears formed cracks at load of 165-225kg (355-490 lb.), inner DCC gears withstood load up to 3,700kg (8,100 lb.).

While positive results on wear resistance were achieved with PS alloy gear-samples tested under engine oil pump conditions, coatings were considered necessary to meet service requirements for transmission pump applications. The range of tested coatings included: (a) non-polymer coatings: Keronite, hard anodizing, hard-nickel plating, Moly-Kote; and (b) anodized-polymer coatings: Nituff, Tufram, and Emralon.

Pumping efficiency improvement and durability of uncoated and coated aluminum-silicon PM alloy gear-samples were tested in a pump test cell at the Engineered Products Division (EPD) of Stackpole Limited using engine oil or transmission fluid, as service media, at temperature about 200^{o}F (~93^{o}C). Gear-samples underwent testing (increased load/speed and accelerated test mode) at conditions simulating high load: speed – 1,600-6,000 rpm, at pressure of 100-160 psi. In accordance with performance efficiency analysis results, clearances may be optimized, and pumping efficiency improvements in the order of 20% at low speeds (most critical operating condition) may be achieved. The evaluation verified 20% horsepower (hp) gains of the aluminum PM gear pump at speed 2,500 rpm and at speed 6,000 rpm, while providing equal pressure and flow at hot idle operating conditions.

Uncoated PS alloy gear-sets exhibited good wear resistance during testing at engine oil pump service environment: at speed 1,600/2,500 rpm and pressure 75/110 psi, up to 500-540 hours. The anodized-polymer coated gears demonstrated no signs of wear at such conditions, and also withstood with minimal signs of wear the increased load/speed and accelerated durability tests in engine oil. Uncoated test gears started to show signs of wear at the increased load/speed testing in transmission fluid at speed 2,500/4,500 rpm and pressure 145/150 psi; accelerated testing also triggered wear of these gears. Abrasive wear caused by aluminum cold welding, exacerbated by high pressure and chemical aggression of transmission fluid appears to be a major point of concern for this application.

Test aluminum gear-samples coated with anodized-polymer coatings demonstrated best durability among tested coatings in both cases, whether coating was applied to one gear (inner or outer) or to the whole gear-set. The gear-sets coated with Tufram or Emralon withstood the increased load/speed testing in transmission fluid without any signs of wear at speed up to 4,500 rpm and pressure up to 150 psi, and had insignificant signs of wear after testing at speed up to 5,900 rpm, and pressure 150 psi. These gear-sets also withstood with minimal signs of wear the 240 hours accelerated durability tests in transmission fluid. Pumping efficiencies sustained through the all durability tests. Future work, therefore, may be focused on design, and customer long term testing.

The following accomplishments have been achieved:

1. DPF team lead supplier, Metaldyne, established the powder premix alloy of aluminum (Al) and silicon carbide (SiC) based on sizing, processability, preform handleability, strength and fatigue

performance criteria for the PMPRA connecting rod.

2. The connecting rod design for aluminum alloy metal matrix composite (MMC) was finalized based on finite element modeling and simulation led by Metaldyne. Metaldyne redesigned the iron (FC-0205) connecting rod for AlMMC powder with a taller shank, thicker pin outer diameter and main bearing cap (crank end) with changes for enhancing fatigue strength.

3. Comparison of the current machined ferrous powder metallurgy connecting rod design and the new Al/SiC design indicated that the Al/SiC connecting rod saves 56% weight. Figure 2-1 illustrates the final geometry and shape of the component.

4. An alternative powder shape consolidation process (that does not require a binder or lubricant additive) for fabrication of forging preforms was developed and demonstrated by Hoeganaes for the model test shape, and evaluations of compaction quality and inter-particle bondings were performed by Ames Laboratory.

5. Tooling for compaction of compacted preforms and sinter-forging of connecting rods was designed and procured by Metaldyne and used for producing over 30 prototype connecting rods for OEM evaluation during Project Year 5.

6. Several commercial powder blending methods were evaluated with suppliers Ames Laboratory, Valimet and Alcoa to optimize processability and handleability of the down-selected premix alloy candidates.

7. The agglomeration supplier, Hoeganaes, demonstrated a commercially feasible, binderless process for powder agglomeration using roll-compaction granulator technology.

8. Specimen fatigue testing at high temperature, and mechanical property and cluster modeling data were developed for the quantitative assessment of material alloy and blend characteristics in DPF PMPRA. Results of room temperature tensile and fatigue property tests and microstructure studies are quite promising, and indicate that it is possible to use sinter-forging methods to develop composites that can perform as well in fatigue as would extruded MMC components.

Overall, this DPF program has demonstrated high potential for using powder metallurgy aluminum composite materials for high-strength lightweight connecting rod applications in volume production. Strength and performance of Al/SiC composite approaching that of extruded MMC was demonstrated. Materials development, processing and handling experience gathered suggest that design rules applicable to ferrous-based materials may need to be revised in order to completely exploit the benefits of using aluminum powder metallurgy composites.

Figure 2-1. 3D Solid Model of PMPRA Connecting Rod

2.3 Deliverables/Products Developed

- PS & DPF Project Final Reports.
- Interactive CD-ROM Design Database developed for use by project participants.
- Prototype gear and connecting rod.

2.4 Technology Transfer Activities

2.4.1 Proprietary Reporting

- Presentations at Annual USAMP AMD Offsites.
- Review meetings among team members documenting technical advances and material/process test results.
- DOE Semi-Annual Technical Report.

2.4.2 Non-Proprietary Publications and Proceedings

[1] Blau, P.J., “The Development of Bench-Scale Test Methods for Screening Aluminum P/M Alloys for Wear Resistance,” in Proceedings of the Powder Metallurgy Aluminum and Light Alloys for Automotive Applications Conference, eds. W.F. Jandeska et al., Metal Powder Industries Federation, Princeton, NJ, pp. 97-106, 1998.

[2] DOE Annual Reports.

3. Hydroforming of Aluminum Tubes (AMD233)

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Team Members:

- Ford Motor Company
- General Motors Corporation
- DaimlerChrysler Corporation
- University of Waterloo
- Alcoa
- Alcan
- VAW
- Eagle Manufacturing
- F&P Manufacturing

Project Duration: December 1999 – December 2002

3.1 Executive Summary

Automotive structural parts can be made from hydroformed tubes. These are tubes that have been bent to shape in a rotary draw bender, and then put into a die where they are expanded by fluid pressure to the configuration of the die. These parts have many advantages over the welded stamped parts they replace: they reduce manufacturing costs (by decreasing part count, dies, welding and scrap) and they improve performance (by reducing mass and increasing stiffness). The automotive industry is finding more applications for steel hydroformed tubes, but the behavior of aluminum during bending and hydroforming is not well understood, and aluminum hydroformed tubes have not been used in the domestic auto industry. The research carried out in this project enabled the safe design and fabrication of hydroformed aluminum tubes, leading to further mass savings and increased fuel economy.

3.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project's goals were to develop material data and computer modeling capability so that hydroformed aluminum tubes can be properly designed and manufactured in a robust process. The project's accomplishments in this time period provided an excellent foundation for this goal. Material properties were determined for welded and extruded tubes of two alloys and two tempers. The project established frictional behaviors for several lubricants and correlated these data with forming performance. Straight tube and bent tube hydroforming were studied experimentally and computationally, as was rotary draw bending. Comparisons of experimental data with simulation results validated the modeling efforts.

Summary of Project Activities and Results:

The project obtained welded Al3.5Mg alloy tubes from VAW and extruded tubes from Alcoa in alloys 6061-T4 and 6061-T6. Tensile data and friction coefficients were obtained for all materials. The team completed free-tube expansion tests to determine formability limits. Straight-tube corner fill tests yielded data on the effect of lubricants during hydroforming into a die. These results correlated quite well with the friction data and also provided more data on material formability. Rotary draw bend tests were also carried out. For all of the forming tests, computer models were built and the results compared with the experimental data. Agreement was sufficiently accurate that the team is confident that modeling can be used in a math-based environment to design manufacturing processes for hydroforming of aluminum tubes.

3.2.1 Computer Modeling Work

Computer models of all of the experiments were developed at the University of Waterloo. The commercial finite element code LS-DYNA® was used in all cases. Experimental friction coefficients were used, with material data determined for the various tube materials. Shell elements and standard material representations for large deformation elastic-plastic materials were used in the simulations. Comparisons with the experimental measurements served to validate the simulations. Sensitivities to parameters such as the friction coefficient were determined.

3.3 Deliverables/Products Developed

Improved simulation technology and hydroforming design products have been developed for immediate automotive applications.

3.4 Technology Transfer Activities

3.4.1 Proprietary Reporting

- Full reports were issued on all project activities and distributed to participants.
- Presentations were made at AMD Offsites.
- Review meetings among team members.
- DOE Semi-Annual Technical Report.

3.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

4. Flexible Binder Control System for Robust Stamping (AMD301)

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Team Members:

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- General Motors Corporation
- DaimlerChrysler Corporation
- Erie Press Systems
- Institut für Umformtechnik der Universität Stuttgart (IFU)
- Ohio State University
- Troy Design and Manufacturing
- United States Steel Corporation
- Pathway Technologies, Inc.
- Sysendes Inc.
- FormSys Inc.

Project Duration: January 2001 – October 2006

4.1 Executive Summary

The goal of the project was to develop and demonstrate, on an industrial scale, an optimized closed-loop flexible binder control system that can be installed in existing presses to improve the quality, reduce the variability, and maintain the accuracy of stampings made from aluminum alloys and ultra high-strength steels. The system can also be used to reduce cost and shorten time for developing and setting production tools. The project ran to the full-scale demonstration stage and assessed the value of the technology in terms of improving manufacturing capabilities and adding robustness to production systems. The next phase would be to quantify the cost savings associated with the implementation of this technology in the stamping plants.

4.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Project 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 an industrial part
- Evaluate technical and economic feasibility of flexible binder technology.

Overall Program Plan:

1. *Retrofit the Erie Binder Load Control Unit*—The Erie Press Flexible Binder Unit was retrofitted with an advanced control system to enable accurate pressure control in all 26 hydraulic actuators during operation in a mechanical press. The system hydraulics was repaired and the electrical system was rewired and retrofitted with a digital real-time control system and appropriate signal conditioning electronics. The unit was tested in a press at TDM using liftgate tooling with both constant and time-varying trajectories and liftgate parts were successfully made from BH210 steel, DP500 steel and A6111-T4 aluminum.

2. *Develop methodology and guidelines for designing and building flexible binders*—In order to determine the stress and strain distribution, structural analyses with ANSYS and analytical static and fatigue strength

calculations were carried out. According to the chosen boundary and load conditions, calculation results have shown the possibility for using the segmented elastic blank holder for long-term usage.

3. *Develop computer simulation and process optimization for flexible binders*—Experiments conducted using the predicted blank holder force indicated that predicted optimum blank holder force gives a very a good starting point for the blank holder force to be applied in try-out and the predicted blank holder force can be quickly refined in try-out to form a quality part without split and wrinkles.

4. *Build and Demonstrate the IFU Binder Load Control Unit with closed-loop system*—Two wrinkle height sensors, a friction force sensor, a blank edge run-in sensor as well as four punch force sensors were integrated into the die set in order to monitor the deep drawing process. The deep drawing process could be controlled nearly independent of input parameter fluctuations by the realization of two closed-loop control circuits which were superimposed on the cylinder pressure control. The results show that parts with identical retention force courses could be produced in spite of different tribological conditions by using friction force control. Flange wrinkles could be avoided or rather limited by employing wrinkle height control.

5. *Demonstrate the Erie Binder Load Control Unit with liftgate tooling*—The tests and demonstrations conducted in this phase of the project showed that flexible binder technology can be used to greatly increase the efficiency of the sheet metal stamping process by virtually eliminating the need for die work. They showed that a large production automotive part with a number of features can be formed with this technology from a variety of hard-to-form materials of different gauges without any die work. In addition, it showed that finite element analysis optimization can be effectively used to provide good initial settings for binder tonnages and reduce the trial-and-error effort needed to determine these tonnages during try-out. The demonstrations also showed that the software is shop-floor friendly and that system produces repeatable results.

6. *Assess the room temperature formability of magnesium alloy sheets*—Preliminary finite element simulations were conducted to check for the feasibility of forming the liftgate part from magnesium alloy AZ31B at room temperature. The flow stress of the material obtained from VPB test was used in the finite element simulation. In the VPB test, the sheet material AZ31B failed due to brittle fracture due to bending at the die corner. Therefore, initially a failure criterion was established to predict the brittle failure of the magnesium alloy sheet material during bending at room temperature from finite element simulation results. The failure criterion was later used to check for the feasibility of forming the liftgate part from magnesium alloy AZ31B at room temperature.

7. *Demonstrate the Erie Binder Load Control Unit with wheelhouse tooling*—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 try-out 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).

4.3 Deliverables/Products Developed

- IFU Binder Load Control Unit with closed-loop system.

4.4 Technology Transfer Activities

4.4.1 Proprietary Reporting

- Review meetings among team members.
- DOE Semi-Annual Technical Report.

4.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

5. Long-Life Electrodes for Resistance Spot Welding of Aluminum Sheet Alloys and Coated High-Strength Steel Sheet (AMD302)

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- DaimlerChrysler Corporation
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- Brush-Wellman
- Nippert Company
- Huys Industries
- Contacts Metals Welding (CMW)
- Tuffaloy
- Oak Ridge National Lab (ORNL)
- University of Windsor
- AK Steel
- Luvata

Project Duration: January 2001 – March 2009

5.1 Executive Summary

Automotive companies have been increasing the use of high-strength steel (HSS) and aluminum for lightweighting automobiles for improved fuel efficiency. Resistance spot welding (RSW) has been the primary method for joining automotive assemblies in mass production. It is estimated that at least 70 billion spot welds are made on vehicles produced in North America annually. While the resistance welding process is cost efficient, substantial cost reductions can be obtained by improving electrode life. However, electrode wear of coated HSS and aluminum has been a continuing and significant problem.

The effects of electrode wear on raw electrode costs, improved productivity, and enhanced product quality can be significant. In order to substantially reduce the costs associated with electrode wear, electrode usage must at least double the existing electrode replacement period for most applications.

5.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Program objectives were to identify and evaluate existing or developmental electrode compositions that could be further developed to double the electrode life of hot-dipped galvanized (HDG) HSS and aluminum production.

Benefits of Improved Electrode Life:

The list of potential areas of cost savings due to improved electrode life include:

- Reduced number of electrodes consumed.
- Reduced labor costs associated with electrode replacement.
- Reduced capital and auxiliary equipment.
- Reduced wear on the equipment.
- Reduced energy usage.
- Improved weld quality.
- Improved production up-time.
- More time available for maintenance, etc.

The annual cost savings estimate for General Motors (GM), Ford, and DaimlerChrysler (DCX) from reduced electrode replacement and labor from doubling electrode life in production was estimated at over $20M per year. Substantial cost savings from other sources should easily more than double the total cost impact. In addition, the lower stepper rates associated with improved stepper schedules requires less energy on a per-day basis. In the beta site tests, daily electrical power usage was estimated to be 18% lower compared than the original electrode and weld schedule.

1. *State-of-the-art benchmarking study—A*ll pertinent data and technologies appropriate for the level of electrode wear were identified. Data on electrode wear phenomena and potential solutions to electrode wear were collected. Existing commercial electrode technologies were identified. This work also involved both a review of open literature and interviews with industry experts. The issues of electrode wear in practice, present solutions, and production constraints were considered in these interviews.

2. *Core testing program*—Electrode life testing using standard techniques were performed to assess specific technologies that were identified in Phase I. Both standard and developmental electrode alloys were tested. A metallographic evaluation of these electrodes was performed. Composition-based technologies that provided improved electrode life were selected for further evaluation. Changes to electrode geometry were considered when warranted by the electrode composition. Serially interrupted electrode life tests were performed for selected technologies. Standard life tests were interrupted after 25, 50, 100, 250, 500, 1,000, and 2,000 welds. At each break point, the electrodes were permanently removed from the holders and assessed using optical and scanning electron microscopy (SEM) metallographic techniques to assess the nature of electrode life improvement using these technologies.

3. *Electrode wear computer modeling—A*n existing computer model of RSW nugget growth at Oak Ridge National Laboratory (ORNL) was adapted for use with galvanized steel. This model was used to make initial assessments of electrode degradation rates.

4. Beta site testing—The data from the electrode life and metallographic testing as well as the computer modeling results were used to select the electrode technologies used in production beta site testing. The site preparations and evaluation techniques were developed as part of the program. Beta site tests were performed at both GM and DCX. Metallography evaluation of these electrodes were compared to previous results.

<u>Problems Encountered</u>:

This project was chartered to study the influence of electrode materials on the electrode life of both aluminum and galvanized HSS. However, after completing several electrode life tests on aluminum with different electrode materials, no demonstrable plan based on electrode composition was clearly highlighted. The factors that contributed to reduced sticking of the tip to the aluminum sheet during electrode retraction were opposite to those which improved weld nugget stability. It became clear that the solutions to improved electrode wear involved much more than an alternate electrode material. As a consequence, the aluminum portion of the work was halted and the focus of the remaining program turned to electrode life of HDG steel.

<u>Conclusions</u>:

The stepper performance of the best-practice electrodes met the program expectations of doubling and tripling electrode life on galvanneal (GA) steel in a production environment. The copper zirconium (CuZr) finned electrode provided up to 24 hour(three shifts) of electrode life under production conditions. The Alloy M electrode provided at least two shifts of useful electrode life under production conditions.

Some additional major findings from work performed in USAMP AMD302 include:

- Male electrodes provided better single-current and stepper-based electrode life compared to female electrode designs

- The stepper slopes on GA steel were much lower and more repeatable than the stepper slopes produced on HDG steel.
- The role of chemical erosion was shown to significantly contribute to electrode face enlargement for specific electrode materials.
- Two approaches to improve electrode life were identified in this program; specifically: (1) electrode design and electrode material that maintained low electrode-sheet interface temperature; and, (2) electrode design and electrode materials that demonstrated a sacrificial nose wear characteristic.
- Substantial correlations were observed between laboratory performance and beta site test results.
- A methodology was developed to generate stepper schedules in production which was used to efficiently compare different electrodes under production conditions.
- Stepper slope rates should increase as the numbers of welds increase in order to maintain current density as the cap face size increases.
- The original electrodes at the DCX beta site were unable to maintain a consistent performance for a two-shift extension of electrode life.
- The best electrodes in this project were the CuZr finned electrodes incorporating reduced face thickness; however, these electrodes were shown in this phase of the work to be machine and application dependent. Specifically, the electrodes were strongly affected by the volume of cooling water.
- The Alloy M electrode incorporating reduced face thickness provided at least two shifts of useful electrode life under production conditions. These were much less affected by water cooling conditions than the CuZr finned electrodes incorporating reduced face thickness.
- Improved electrode life results in significant cost savings due to power reduction, improved process robustness, and electrode replacement costs.

5.2.1 Computer Modeling Work

Because of the extensive computing time required to repeatedly run and incrementally update the electrode conditions in the model, a simpler model focusing on only deformations at the electrode face was developed. The ORNL model was used to describe the deformation of the electrode face during electrode wear. The temperature-dependent physical properties for several copper alloys were needed for the model. These were also developed at ORNL as part of the project. An independent analytical model was also developed at EWI that examined the rate of deformation at the electrode face as a function of welding parameters, material properties and electrode geometry. The results from these deformation models were compared to the experimental data from Phase II.

Another model was also developed at ORNL that described the compositional and micro-structural changes that occur between zinc and copper at electrode-sheet interface temperatures. This model described the rate of alloy development and growth. It was used to describe the deposition portion of electrode wear. The temperature-dependant physical property inputs were developed as part of the program. These results from the deposition model were compared to the metallographic data from Phase II.

5.3 Deliverables/Products Developed

- Database on electrode performance and various computer models as described in Section 5.2.1.

5.4 Technology Transfer Activities

5.4.1 Proprietary Reporting

- Peterson, W., "Literature Review of RSW Electrode Wear," Report to USCAR, EWI Project No. 45287CSP (March 28, 2002).
- Peterson, W. and Gould, J., "Electrode Life of Several Commercial and Developmental Electrodes for High-Strength Galvanized Steel and Aluminum," Report to USCAR, EWI Project No. 46106CSP (November 12, 2003).
- Peterson, W. et al., "Sequential Life Testing of Developmental and Standard Spot Weld Electrode Alloys on Hot-Dipped Galvanized Steel," Report to DaimlerChrysler Corporation, EWI Project No. 46829CAP (August 31, 2004).

5.4.2 Non-Proprietary Publications and Proceedings

[1] Athwal, B., "Characterization of Electrode Wear Morphology via Sequential Life Testing," M.A.Sc. Thesis, University of Windsor, Windsor, ON, 2005.

[2] Babu, S. et al., "Modeling of Resistance Spot Welding Electrode Life," Sheet Metal Welding Conference XI, Paper 7-2, Sterling Heights, MI, AWS – Detroit Section, May 11-14, 2004.

[3] Caron, J. L., "Laboratory and Production Testing of Novel Resistance Spot Welding Electrodes," M.A.Sc. Thesis, University of Windsor, Windsor, ON, 2006.

[4] DOE Annual Reports.

6. NDE Tools for Evaluation of Laser-Welded Metals (AMD303)

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- DaimlerChrysler Corporation
- The Edison Welding Institute (EWI)
- National Center for Manufacturing Sciences
- Lawrence Berkeley National Lab (LBNL)
- GE Inspection Technologies
- Kuka Flexible Production Systems

Project Duration: January 2001 – March 2005

6.1 Executive Summary

The objectives of the AMD303 project, NDE Tools for Evaluation of Laser-Welded Metals, were to evaluate and develop fast, accurate, robust, non-contact non-destructive evaluation (NDE) tools and methodologies to:

- Eliminate or minimize the use of manual destructive testing of laser lap-welded sheet metal structures.
- Eliminate or minimize the need for highly-trained/experienced NDE evaluators
- Demonstrate the accuracy and repeatability of technology developed or applied.

This project had two primary investigative missions:

1. Evaluate and develop new NDE tools for laser-welded steel (zinc or organically coated).

2. Evaluate and develop NDE tools for laser-welded aluminum.

The investigative strategy was to:

- Conduct a comprehensive assessment of existing and emerging NDE tools for steel and aluminum.
- Down-select to the most promising NDE technologies for the chosen laser-welded application – a roof-ditch rail component assembly.
- Conduct validation testing of the NDE technologies on fabricated weld coupons, production laser-weld samples and production laser-welded parts.
- Develop, test and demonstrate new or improved technology(ies) in a prototype system on production laser-welded parts.

6.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The NDE Tools for Evaluation of Laser-Welded Metals project was divided into two primary phases.

In Phase I the emphasis was on an identification and evaluation of suitable NDE technologies for the chosen laser-weld application, the roof-ditch rail. Phase I involved the following activities:

- Assessment of state-of-the-art of NDE technologies and identification of the laser weld discontinuities features of interest.
- Down-selection of technologies to those believed capable of inspecting the roof-ditch rail application.
- Comparative technology testing on fabricated weld coupons in steel.
- Correlation of NDE test results with destructive test results.
- Technology selection for Phase II prototype development and testing.

Ultimately, two technologies were selected for their capabilities for detecting weld discontinuities judged essential by the AMD303 project team. The two NDE systems, an ultrasonic electromagnetic acoustic transmitter (EMAT) and an ultrasonic through-transmission roller scanner, performed comparably well. The evaluations indicated both systems required additional development and reconfiguration to perform acceptably well in the original equipment manufacturer production environment and on the roof-ditch rail application. Ultimately, primarily due to cost advantages over EMAT ultrasonics associated with prototype development and the eventual selling price, the ultrasonic through-transmission roller scanner technology was selected for Phase II prototype development and evaluation.

In Phase II of the project, the ultrasonic roller scanner was modified in both hardware design and in software based on our needs, and subjected to extensive testing on fabricated steel and aluminum coupons of varying joint geometries and vehicle roof-ditch rail parts fabricated for evaluation purposes. Phase II involved the following activities:

- Prototype I testing using laser-welded steel coupons, vehicle parts in steel and fabricated laser-weld coupons in aluminum.
- Evaluation, redesign and modification of the prototype for the roof-ditch laser-weld application (Prototype II).
- Validation and correlation of Prototype II test results with other NDE test data and destructive test results.

<u>Project Conclusions</u>:

Laser welding is viewed as a joining technology that will facilitate the use of lightweighting materials and designs. The development of NDE tools is viewed as an enabling technology allowing the reduction of vehicle mass through increased use of laser welding of lightweight materials in automotive plants.

Ultrasonic through-transmission technology shows promise for use on the roof-ditch application. Lack of fusion (LOF) and skips over 6mm in length were clearly detectable, both the designed skips between weld segments (stitches) and LOF induced by placing a shim between the steel sheets or by varying the laser welding parameters. Ultrasound transmission found every skip and LOF in the Ford Motor Company Chicago Assembly Plant 1st field test (CAP-1) and the Chicago Assembly Plant 2nd field test (CAP-2) roof-ditch weld samples. Furthermore, the amplitude signal and encoder tracking values allowed one to distinguish designed skips occurring between stitch welds from LOF happening where a weld was originally intended.

<u>Lessons Learned</u>:

Making coupons for testing and evaluation purposes is not a trivial task. An appreciation was acquired for understanding the materials, the cleaning and welding of those materials, real-world joint geometries, how discontinuities naturally occur, how they can be induced by artificial means, and whether they are within the detection capability limits of the testing device and able to yield valuable knowledge.

Attempting to translate the laboratory testing and findings cited in this report directly to the field testing and findings in this project is not advisable. While operator-induced rolling forces are seen to produce amplitude variances in the laboratory, additional influences are seen in the field, including:

- Fatigue caused by standing atop a ramp and having to walk along the ramp the entire length of the vehicle, all the while maintaining a constant pressure on the dry-couplant wheels on both the roof and body-side surfaces, keeping the roller scanner aligned with the changing width of the roof-ditch sides, and simultaneously assuring the continuous capturing of all data points for the full length of the scan. The effects of these conditions on the field trial results are unknown, but intuitively we now know that this application is best suited for a robotic implementation in order to eliminate as many of these contributors to signal variance and degradation as possible.

A large database will be needed to create algorithms for a “smart” NDE interface with weld quality decision and weld-sizing functions, and to address issues such as:

- Significant numbers of traces of good welds, skips, and welds containing LOF and other discontinuities to permit analyses based on frequency differences from the “good weld” signals.
- Collection of physical teardown results to initially correlate and then periodically validate NDE data generated during testing of a part.
- Developing the algorithms needed to automatically measure percent of good weld will require a clear understanding of the weld signal levels that are to be measured as part of total weld length. Additional correlation studies of such data with other NDE validation techniques and physical measurement after teardown will confirm how strong the reflected signal has to be, to be considered as part of the total weld length calculation.

Utilizing sample sizes statistically large enough to yield reliable interpretation of data may have been adequate for this study, but much larger sample sizes are needed to establish the confidence levels needed for installation in OEM plants, including:

- Sufficient numbers of production roof-ditch rails and interval skip-stitch welds for detection reliability and measurement correlations.
- Significant numbers of traces to establish reproducibility and repeatability either for multiple operators or for multiple traces performed by an automated implementation.

6.3 Deliverables/Products Developed

- Database of NDE tests on weld coupons.
- Various prototypes of generic weld geometries.

6.4 Technology Transfer Activities

6.4.1 Proprietary Reporting

- Project results were communicated at the USAMP Offsite Annual Meetings, to DOE in Semi-Annual and Annual Reports, and in this Final Report.

6.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

7. Magnesium Powertrain Cast Components (AMD304)

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- Intermet
- Lunt
- Meridian
- Memak
- Spartan
- Thixomat
- Gehring
- Flame Spray
- Becker
- Delaware
- EXCO
- HE Vannatter
- Ashland/Valvoline
- Chevron Texaco
- Honeywell/Prestone
- INTAC
- RIBE
- Dana/Victor Reinz
- Amalgatech
- CANMET
- Stork
- Welstmoreland
- Quasar
- EKK
- Flow Science
- MAGMAsoft
- Technalysis
- IMA
- NADCA
- Reid and Associates
- Ford Motor Company
- General Motors Corporation
- DaimlerChrysler Corporation

Project Duration: January 2001 – 2011

7.1 Executive Summary

The Magnesium Powertrain Cast Components (MPCC) was established to provide comprehensive answers to questions regarding the technical feasibility and cost-benefit ratio of using magnesium in powertrain components. Although magnesium has been demonstrated to significantly reduce weight at acceptable cost in many areas of the vehicle, structural powertrain components have not benefited from this material. The reasons for this are as follows:

- The high cost of alloys that can withstand the operating temperatures of the engine without deforming under load (creeping).
- Limited powertrain design experience with magnesium alloys.
- Lack of long-term field validation or controlled-fleet testing data for magnesium powertrain components.
- The limited scientific infrastructure in the U.S. that is directed toward acquiring a fundamental understanding of magnesium alloys and casting processes.

If successful, the weight reduction benefits of magnesium will ultimately be realized in powertrain applications with subsequent fuel economy and emissions benefits accruing to the environment and the national economy.

7.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Whereas the plan for the original team make up was the original equipment manufacturers and about 20 other organizations, by the end of the first year, 34 organizations had committed to the project objectives and their willingness to participate in the project. The project ended with a total of 42 participants. This, combined with the OEM commitments and the support from DOE ensured the necessary funding for the MPCC project, and that this project could be accomplished with the necessary breadth and depth of expertise to provide a comprehensive answer to the question of the readiness of magnesium for powertrain applications.

- Demonstrate and enhance the feasibility and benefits of using magnesium alloys in engine components.
- Design an ultra-low weight, cost-effective performance-engine block, front engine cover, and structural oil pan using the best low-cost, recyclable creep and corrosion-resistant magnesium alloys.
- Compare and select the alloys on the basis of common-protocol casting and testing. (The resulting cast specimen database will provide the necessary design data for the components.)
- Design and build the component tools.
- Cast and test the components in operating powertrains.
- Validate the performance benefits, component durability, and system costs.
- Create a material specification for magnesium powertrain alloys common to original equipment manufacturers.
- Identify critical challenges for future magnesium alloy and component deve-lopments and use this information to promote scientific research in the U.S.

There were six tasks in the project plan:

1. *Benchmark the properties of promising high-temperature magnesium alloys*—Nine alloys cast and property measurements completed; electronic database architecture completed; castability and corrosion tests completed; pair-wise analysis methodology used to select alloys for each of four engine components.

2. *Design of magnesium intensive V6 engine*—FEA design and CAD models completed; weight reduction target exceeded; cost model completed; U.S. Utility Patent 7284528 issued to USAMP for crank shaft support assembly.

3. *Strengthen scientific infrastructure*—Six critical areas for research identified; from RFPs, five new projects started and completed involving five different North American universities/laboratories.

4. *Cast components for magnesium-intensive engine*—Tools designed and built; component casting for cylinder blocks, structural oil pans, front engine covers, and rear seal carriers completed. Cylinder bore coating development completed.

5. *Measure and integrate excised specimen tensile properties to the ALM database*—Completed.

6. *Evaluate design, performance, durability, and cost-effectiveness of magnesium-intensive engine*—Component testing completed with refinements applied. Durability test of magnesium oil pan and front cover on aluminum block completed. Hot and cold scuff engine tests completed – engines passed. Bulkheads broke during first durability test startup; probable cause is weak interface between iron inserts and magnesium bulkheads. Low engine load coolant durability test in set-up.

Phase I of the project resulted in the engine design and the technical requirements for the magnesium alloys that would be used for each of the cast engine components. Six high-pressure die casting and three sand casting alloys were cast into specimens for measurement of thermo-physical properties, static and cyclic mechanical properties (including creep), and corrosion resistance in atmosphere and in coolant formulations. Four major coolant suppliers provided ethylene glycol-water coolants with proprietary magnesium protective additives. All castings were done using ht same tooling and in the same melting and casting systems to enable common protocol comparison. The results of the above testing have been placed in an electronic database that has been distributed within the project team membership and is being rolled out to the industry (AFS, 2010). Major achievements in mass reduction are shown in Figure 7-1.

Having (1) completed the engine design and a technical cost model; (2) shown that both mass reduction and cost targets were being met; and (3) that there were commercial, creep-resistant magnesium alloys with the properties required for the design; Phase II of the MPCC project was approved and launched. In Phase II, (1) alloys were selected for each magnesium engine component; (2) tooling was designed and built; (3) the magnesium components were cast; (4) the blocks were machined and the bores coated with wear-resistant Fe/Fe); (5) and the engines assembled and tested. Additional work included the initiation of the five research projects to address potential knowledge gaps and to support the magnesium scientific infrastructure in North America. The work in Phase II was completed in 2009.

The MPCC project accomplishments with respect to the original project objectives are consistent with the project vision that the magnesium-intensive powertrain was cost-effective, durable and has demonstrable performance benefits.

Component	Production Al Duratec kg	MPCC Mg-intensive kg	Mass Reduction kg (percent)
Block assembly	32.2	24.0	8.2 (25%)
Oil Pan	4.4	3.2	1.2 (27%)
Front Cover	5.6	2.6	3.0 (53%)
Total for 3 Cast Components	42.2	29.8	12.3 (29%)
Complete, dressed Engine	176.8	163.0	13.8 (8%) 29 pounds

Figure 7-1. Mass of Individual and Assembled Engine Components for Baseline Aluminum Engine (Duratec) and the MPCC Magnesium-Intensive Engine (Mass reductions achieved as indicated)

Demonstrable Performance Benefits:

- The mass reduction target was 15% for the cast parts that were converted from aluminum to magnesium. Figure 7-1 shows that the realized mass reduction was 29%, nearly twice the target.
- Noise and vibration was expected to be significantly increased by replacing aluminum with magnesium. Instead noise vibration testing determined that the aluminum and magnesium oil plan and front engine covers emitted nearly the same dBA. The magnesium block however was nearly 6 dBA louder at the most susceptible engine rpm, but most of this increase was attributed to the design of the block (deep skirt with unrestrained skirt walls) rather than the change in material from aluminum to magnesium.

Durable:

- Component testing comprising thermal cycling and thermal aging of the block showed neither loss of bolt load retention nor changes in block bore cylindricity or overall dimensions (growth).
- Hot scoff and cold scuff engine testing showed that the piston/ring system was appropriate for the high CTE magnesium bores and that the wear-resistant bore

coatings were adherent and would be durable for engine testing.

- A 675 hour durability test of the magnesium front engine cover and oil pan on an aluminum block showed no damage to the magnesium components, not bolt load loss (creep), and no corrosion.
- A 672 hour engine test for coolant corrosion show that ethylene glycol-water with magnesium protective additives could be effective. Teardown inspection of the block revealed light frosting of the internal surfaces with corrosion product, but the coolant remained clear of corrosion product and had acceptably low levels of iron, zinc, and magnesium ions.
- An engine being prepped for deep thermal shock testing failed during break-in. Analysis attributed the failure to the absence of a metallurgical or mechanical bond between the iron inserts and the magnesium bulkhead. Finite element analysis showed ways to avoid this in future designs.

Cost-Effective:

The mass reduction cost target was < $2 per pound mass reduced. At the highest prices of magnesium during the project period, the realized cost was ~$4 per pound. However, the cost models showed 80% of this cost to be magnesium ingot cost. Using the prices of magnesium when the original target was set, the realized cost of mass reduction was ~$2.30 per pound, which is very close to the original target.

Problems Encountered:

The profound problem that the MPCC project encountered in its first year was that whereas the original project was developed around a magnesium transmission, circumstances beyond the control of the project forced a refocusing of the project to the engine, instead of the transmission. From a technical and an economic perspective, this change necessitated expanding the scope and complexity of the design effort, the test program, and the cost model.

Conclusions:

No show stoppers were identified in the course of this project. All expected technical challenges either were solved within the project or were shown to have solutions in future products. However, magnesium prices remain high and volatile. This is the main risk to the realization of the MPCC project team vision. But even at the highest prices encountered during this project, the cost of mass reduction was still within the guideline that if less than the price in U.S. dollars of a gallon of gas, then mass reduction is economically feasible.

7.3 Deliverables/Products Developed

- Cast magnesium specimen property and processing database in electronic form by American Foundry Society.
- Common material specification for magnesium powertrain alloys.

7.4 Technology Transfer Activities

7.4.1 Proprietary Reporting

- Review meetings among team members.
- DOE Semi-Annual Technical Report.
- U.S. Utility Patent 7284528 issued to USAMP for crank shaft support assembly

7.4.2 Non-Proprietary Publications and Proceedings

[1] Powell, B.R., "The USAMP Magnesium Powertrain Cast Components Project," 12th International Magnesium Association Automotive Magnesium Seminar, Troy, MI, April 10, 2001.

8. An Improved A206 Alloy for Automotive Suspension Components (AMD305)

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- GKS Engineering Services
- Thyssen Krupp Stahl Specialty
- Westmoreland Mechanical Testing and Research
- Alcan
- Intelligent Sensing Technologies

Project Duration: January 2001 – April 2002

8.1 Executive Summary

In 1909 Alfred Wilm discovered that an Al-4.5%Cu-0.5%Mn alloy would strengthen, by aging after a quench from an elevated temperature. This alloy was called "Duralumin," and formed the basis for the Al-Cu family of casting alloys. The Al-Cu based alloys have excellent mechanical properties, high-temperature strength, and low-cycle fatigue properties; but they are difficult to cast. Their long freezing range makes them susceptible to hot cracking. It was discovered that a low titanium content version of 206 alloy gave a smaller grain size, and has improved hot crack resistance. Consequently, casting trials were undertaken in this project to pour two different control arms with the new 206 alloy. Both parts were made successfully. Also, a new ultrasonic inspection method was found to provide a fast, real-time determination of the presence of cracks.

The 206 alloy is significantly stronger than the premium quality alloys used today for automotive castings, and has mechanical properties approaching some grades of ductile iron. It also has excellent high-temperature properties and low-cycle fatigue strength. Consequently, this material can 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, 206 alloy is seldom used, primarily because of its propensity for hot cracking. An improved method to grain refine this alloy was developed, which reduces its tendency for hot cracking. Also, a new ultrasonic inspection technique to test for cracks was tested in this project. Two control arms were produced to establish the viability of this material for automotive suspension components, and a complete battery of mechanical property tests was conducted on the castings. A set of design guidelines was also compiled which engineers may use to produce components from this high-strength material. The results from this project make it possible for automotive design engineers to produce suspension components in B206 alloy, and to produce lighter, more fuel efficient automobiles.

8.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

This project consisted of the following sub-tasks:

- Phase I – To establish the feasibility of producing crack-free automotive suspension components with a new 206 alloy, using the permanent mold casting process.

- Phase II – Once feasibility is established, to optimize the casting process for a control arm casting, and to produce sufficient quantities of this part for Phase III and IV studies.
- Phase III – To conduct a full spectrum of mechanical property measurements, including tensile and fatigue tests, precision modulus, fatigue crack growth rate, and stress corrosion tests.
- Phase IV – Evaluate a new ultrasonic inspection technique for crack detection in the control arm castings.
- Phase V – Prepare detailed design and production guidelines for 206 alloy castings, which engineers can use to minimize formation of hot crack defects.

All phases of this project were completed successfully as outlined in the accomplishments below:

- Casting trials were undertaken in this project to pour two different control arms with the new 206 alloy. Both parts were made successfully as shown in Figure 8-1.
- A new ultrasonic inspection method was found to provide a fast, real-time determination of the presence of cracks.
- This project shows that it is possible to produce suspension components in 206E alloy, using the tilt-pour permanent mold process, to acceptable low levels of scrap.
- Mechanical properties obtained in castings made with the improved 206 alloy are significantly higher than those found with the conventional A356 alloy. In fact, the tensile strength of 206E alloy is equal to some grades of ductile iron. The low-cycle fatigue life (at fixed load) is almost 10 times that of A356 alloy. This new material may therefore be used to save weight in automobiles, and improve fuel economy.

8.3 Deliverables/Products Developed

- Prototype control arms.
- Detailed design, production and non-destructive evaluation guidelines for 206 alloy castings.

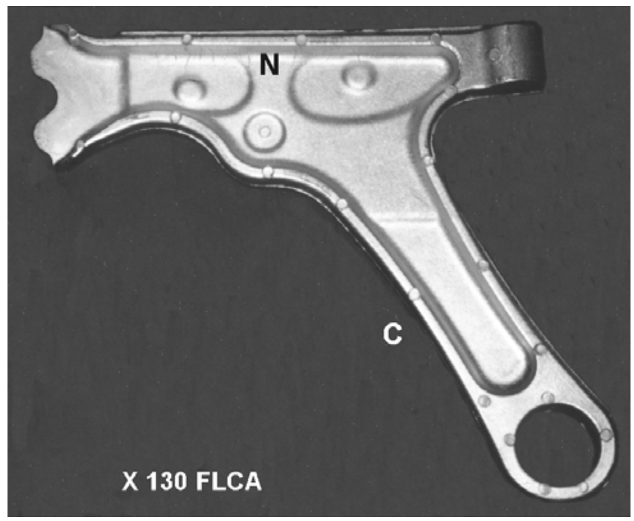

Figure 8-1. Control Arm Casting Demonstrated from Improved 206 Alloy in Permanent Mold Process

8.4 Technology Transfer Activities

8.4.1 Proprietary Reporting

- Review meetings among team members.
- DOE Semi-Annual Technical Report.

8.4.2 Non-Proprietary Publications and Proceedings

[1] The new, improved 206 alloy has been registered as B206 alloy with the Aluminum Association. B206 alloy is now being used commercially for a number of high-strength components.

[2] Sigworth, G.K. et al., “Use of High-Strength Aluminum Casting Alloys in Automotive Applications,” Light Metals 2001 Métaux Léger, eds. M. Sahoo and T.J. Lewis, Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, Quebec, 2001. Received the 2001 Light Metals Best Paper Award by the Canadian Institute of Mining and Metallurgy.

[3] Sigworth, G.K., “High-Strength Casting Alloys for Automotive Applications,” accepted for presentation at Automotive Alloys – 2002 TMS Conference.

[4] DOE Annual Report.

9. Plasma Arc Spot Welding of Lightweight Materials (Aluminum and Magnesium) (AMD306)

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- DaimlerChrysler Corporation
- Arc Kinetics, LLC
- Rite-On Industries, Inc.
- ALCAN
- ALCOA
- AlcoTec
- LaManna Enterprises

Project Duration: January 2001 – April 2005

9.1 Executive Summary

In 1999 Arc Kinetics, LLC teamed with a major European auto manufacturer to evaluate its plasma technology for the production of cosmetic joints on an all aluminum monocoque body of a recently launched model. The super-structure of this vehicle is produced through a use of adhesive bonding and self-pierce riveting method. While the plasma arc AC-Thermospot technique was devised too late for adoption on this vehicle, both the manufacturer and Alcan encouraged Arc Kinetics to pursue the tech-nology as riveting and bonding was considered expensive, especially for lower priced, higher volume vehicle models. With the advent of additional interest by both General Motors and DaimlerChrysler it made most sense to approach the PNGV group to assist with furthering the lightweight materials joining issue.

The purpose of this project was to develop and verify the joining technology required for joining lightweight materials (aluminum and magnesium). This would be accomplished through a comprehensive evaluation and product performance of plasma arc spotwelding of aluminum and magnesium in its various forms (sheet, casting and extrusion) for high-volume automotive production.

9.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Main Project Findings:

- Absorbed hydrogen compounds (i.e. hydrated oxides) present in the surface film of sheet aluminum at present demands the application of a phosphoric acid based pretreatment prior to plasma arc spotwelding, if voids in the form of haloes are to be eliminated.
- Microcracking within the plasma arc spotwelds appears to be eliminated through the addition of appropriate amounts of 4047 grade filler material.
- Destructive testing of spotwelds by the torsional shear method can be invaluable in assessing the likely strength; degree of macroporosity and material thinning through outgassing effects in such welds and this evaluation method allows optimization of weld parameters.
- Plasma arc spotwelds, with their inherently larger nugget sizes typically offer tensile shear strengths 40% higher than competitive technologies.
- Under alternating current welding conditions (as used in this project) damage to the plasma torch nozzle through double arcing can be prevented with a convex radiussed tip geometry.

- Service intervals in excess of 3,000 welds can be achieved for the consumables associated with the plasma arc spotwelding process. This is greatly in excess of service intervals associated with resistance spotwelding of lightweight materials.
- Hard anodizing of an aluminum shield cup of appropriate design can give a lower cost, more robust product than the ceramically coated copper alloy shield cups previously associated with the process when used in its direct current form.
- A flat surfaced back up positioned between 0.75mm and 1.0mm below the lower sheet surface gives improved performance in terms of weld quality compared to alternative geometries.
- Magnesium testing and sectioning identified the importance of addition of the correct volume and type of filler material plays in producing a robust weld. This reflects that much of what was learned during the welding of the aluminum material is applicable to the plasma arc spot welding of magnesium.
- The plasma arc spotwelding process shows potential for the joining of magnesium sheet.

9.3 Deliverables/Products Developed

- A robust process to join lightweight materials economically.

9.4 Technology Transfer Activities

9.4.1 Proprietary Reporting

- Review meetings among team members.
- DOE Semi-Annual Technical Report.

9.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

10. Warm Forming of Aluminum II (AMD307)

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- DaimlerChrysler Corporation
- National Center for Manufacturing Sciences
- Ricard Meda
- Pechiney Rolled Products – Alcan
- Jay & Kay Manufacturing
- Fuchs Lubricants
- Troy Tooling Technologies
- Atlas Tool, Inc.
- University of Michigan
- Camanoe Associates
- Infrared Technologies
- Sekely Industries

Project Duration: January 2001 – December 2006

10.1 Executive Summary

The potential of warm forming technology to significantly improve the formability of aluminum was previously demonstrated in a separate study. An aluminum Dodge Neon door inner was formed with one die and one hit, providing convincing evidence of the feasibility of the warm forming concept.

Approved for incorporation into the USAMP/AMD project portfolio in 2001 with completion in December 2006, the objectives of the AMD307 Phase II project, Warm Forming of Aluminum II, were to develop and demonstrate a full scale warm forming process for the forming of aluminum sheet for automotive body structures, and determine the financial viability of the warm forming process for a production environment using a technical cost model.

10.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The previous warm forming 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 warm forming technology to significantly improve the formability of aluminum using a specially-processed 5000 Series aluminum alloy containing manganese and magnesium. The Phase I study used a conventional stamping die retrofitted with heaters thought to be sufficient for use in warm forming (Figure 10-1).

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.

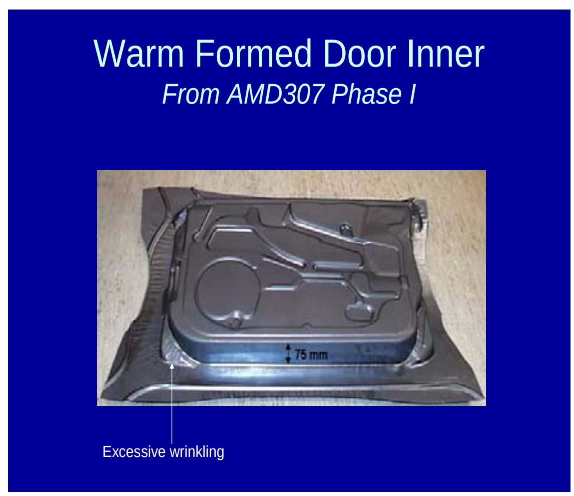


Figure 10-1. Warm Formed Door Inner Made in Phase I Die Showing Excessive Wrinkling and Sheet Distortion

The technical approach was to:

- Develop and evaluate individual elements of the warm forming process first in a laboratory environment including alloy characterization, forming lubricants, forming simulations and process thermal modeling.
- Develop full-size demonstration of warm forming process and run test trials in a press-shop environment. Process design included planning for blank pre-heating, lubricant application, press and die with warm forming 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 aluminum 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 aluminum alloys, specifically AA5182-O, were achieved through development of warm forming process advancements in Phase II as discussed below:

- *Constitutive equation* was developed for AA5182-O for formability simulations that allowed design of warm forming pan die and definition of warm forming process parameters.
- *Cleanable lubricant* suitable for use in a warm forming 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 warm forming trials.
- *Rapid conduction pre-heating 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 pre-heater and material handling automation. A conventional conduction oven was made available to pre-heat the blanks for the warm forming trials and the blanks were moved manually, thereby allowing the project to remain within budget.
- *Warm forming 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 warm forming process, but conclusively proved that a controlled warm forming process cannot be achieved using a conventional stamping die refitted with heaters, as was the door inner die shown in Figure 10-2.
- *Purpose-built warm forming pan die* was designed using computer-aided engineering simulation tools (finite element analysis) and knowledge gained from monitoring and analyzing thermal behaviors during the door inner warm forming trials utilizing the modified Phase I die. This purpose-built pan die provided thermal stability and uniformity (Figure 10-3).
- *Warm forming 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 250°C, binder at 300°C with the punch at 250°C, and entire die at 350°C. Full pans, 125mm deep, were stamped at the latter two conditions without splitting or wrinkling. Trials were performed to understand the effect of blank pre-heat temperature and lubricant type as well as to provide a preliminary understanding into the performance of magnesium sheet.

- *Technical cost model* was developed and used to evaluate and optimize the Phase II process design and to compare process cost of warm forming of aluminum parts to similar parts fabricated in steel by conventional stamping methods. The model can be applied to future process designs.

Conclusions:

The warm forming pan die trials conducted in October 2006 successfully demonstrated the formability improvements that can be obtained by forming aluminum sheet at elevated temperatures. Blanks were pre-heated 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 warm forming could be performed. It also enabled comparison of lubricants and various materials. Some specific conclusions are:

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

10.3 Deliverables/Products Developed

- Formability process window.
- Purpose built pan die.
- Warm forming lubricant.

10.4 Technology Transfer Activities

10.4.1 Proprietary Reporting

- Project results were communicated at the USAMP Offsite Annual Meetings and to DOE in Semi-Annual Reports and in this Final Report.

10.4.2 Non-Proprietary Publications and Proceedings

- Two documents were approved by the individual original equipment manufacturers and AMD307 Committee for submittal to professional journals.
- Project progress and results were submitted to DOE in Annual Reports, which were approved for public dissemination.

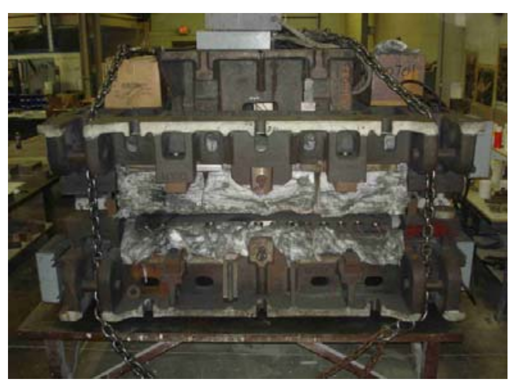
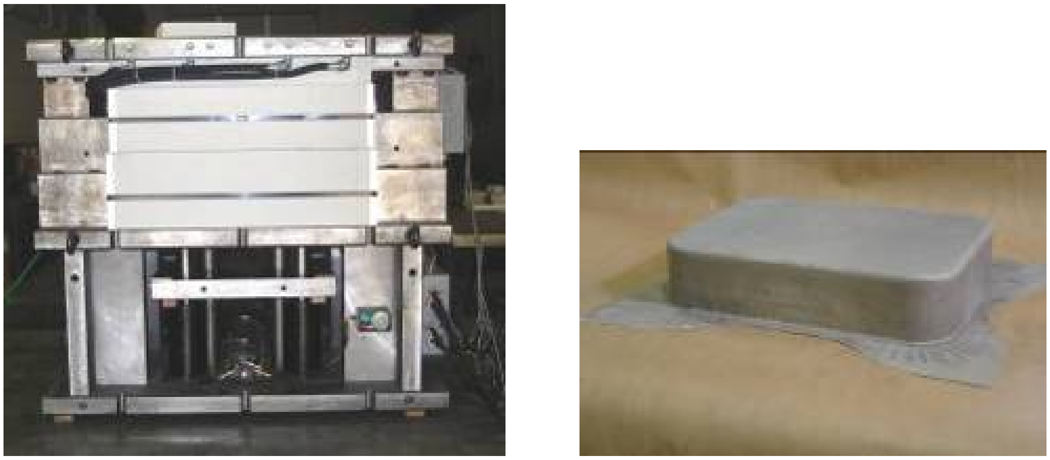


Figure 10-2. Conventional Stamping Die Refitted for the Warm Forming Feasibility Study Performed in Phase I



(a) (b)

Figure 10-3. (a) Photograph of the Warm Forming Pan Die Used in Phase II Study and (b) Typical Pan Produced by the Die

11. Exploratory Study into Improved Formability and Strength of Automotive Aluminum Sheet Alloys with an Electric Field (AMD308)

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Project Duration: January 2002 – January 2004

11.1 Executive Summary

To reduce weight and thereby improve fuel economy, auto makers are considering aluminum alloys for automobile body panels. Aluminum alloys, however, have lower formability than mild steel. Since in prior work it had been found that an electric field had an influence on the microstructure and properties of aluminum alloys, it seemed desirable to investigate the possibility that the application of an electric field might be beneficial regarding the formability and strength of automotive aluminum alloys. The objective of the present research project was, therefore, to perform an exploratory study into the potential for improving the formability and strength of aluminum sheet alloys by applying an electric field during processing or during forming.

The first phase of the project, January – September 2002, results determined that an external DC electric field of 5kV/cm applied during *the solution heat treatment* of 6061 aluminum alloy at 525°C increased the tensile elongation of the T4 temper by a factor of 36% with a gain of 8% in the tensile strength. Also, the application of an electric field of the same magnitude to *as-quenched* 6063 W at room temperature gave an increase by a factor of 15-17% in the elongation without loss in strength. Moreover, it was established that specific correlations existed between the non-destructive test measurements of electrical resistivity and hardness and the tensile strength of the alloys.

In continuation of the research project, the effort focused on two additional aluminum sheet alloys, namely AA6111 and AA5182, which are of special interest to the automotive industry.

11.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

AA6111 – the following effects of an external DC electric field were investigated:

1. *Applied during solution heat treatment (SHT) as a function of the SHT temperature*—Exposure to an electric field during SHT at 500-550°C increased the tensile strength of the subsequent natural-aged T4 temper by 2-8%, the hardness by 10% and the elongation by a factor of 2-11%. As a corollary the SHT temperature was reduced by 10-26°C for a constant strength.

2. *Applied to as-received T4 sheet at room temperature (RT)*—Exposure of the as-received AA6111-T4 to an electric field for 24 hours at RT gave an increase of 10% in tensile strength and increased the elongation by a factor of 4.5%.

3. *Applied during tensile straining of as-received T4 sheet at RT*—Exposure of the as-received AA6111-T4 sheet to an electric field during a tensile test to fracture gave an increase of 11% in tensile strength and increased the elongation by a factor of 6 %.

4. *Applied during plastic deformation of as-received T4 sheet at RT and then aged at 175°C without field*—Determined that the effect of the electric field during SHT was to reduce the enthalpy and entropy of solution of Mg_2Si in aluminum, but not the Gibbs free energy. This indicates that the field altered the nature, form or distribution of the soluble Al-Mg-Si complex rather than changing the amount in solution.

5. Determined the correlations between resistivity, hardness and tensile strength for natural aging from the W to the T4 temper.

AA5182, the following effects of an external DC electric field were determined:

- Applied to the as-received O-temper sheet at room temperature (RT), 100°, 150° and 200°C.
- Applied during the tensile deformation of the as-received O-temper sheet at RT.
- Applied during plastic deformation of the as-received O-temper sheet and then aged at 175°C without field.

No effect of an electric field was found for the conditions investigated. It is however suggested that the application of an electric field during processing (i.e. during homogenization, rolling or annealing) might have a beneficial effect.

11.3 Deliverables/Products Developed

- Reports on feasibility of using electrical field during forming of aluminum sheet.

11.4 Technology Transfer Activities

11.4.1 Proprietary Reporting

- Conrad, H. and Manning, Jr., C.R., “Exploratory Study into Improved Formability and Strength of Automotive Sheet Alloys with Electric Field,” U.S. Automotive Materials Partnership, Contract No. DE-AC05-020R22910, FY 2002 Progress Report.
- Conrad, H. and Manning, Jr., C.R., ibid., USAMP Project #AMD308, Quarterly Report for the Period October 1-December 31, 2002.

11.4.2 Non-Proprietary Publications and Proceedings

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[2] Swalin, R.A., Thermodynamics in Solids, John Wiley and Sons, New York, 1962.

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[6] Mott, N. F. and Nabarro, F. R. N., *Proc. Phys. Soc.*, Vol. 52, p. 86, 1940.

[7] Friedel, J., Dislocations, Addison-Wesley, Reading, MA, 1967.

[8] Kelley, A. and Nicholson, R. B., *Prog. Mater. Sci.*, Vol. 10, p. 151, 1963.

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12. Aluminum Automotive Closure Panel Corrosion Test Program (AMD309)

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- Mike Wheeler, Consultant
- Elzly Technology Corporation
- Ford Motor Company
- General Motors Corporation
- Henkel Corporation
- National Exposure Testing
- Navy Laboratory Carderock, Bethesda
- PPG Industries, Inc.
- Quality/Statistics
- Singleton Corporation
- University of Western Ontario, Surface Science Center

Project Duration: June 2000 – March 2010

12.1 Executive Summary

The objective of the AMD309 project has been to develop or identify a standardized accelerated corrosion test which predicts cosmetic corrosion field performance on finished aluminum body panels. Panel sets were created to include different aluminum alloys and processing conditions known to cause variation in field corrosion performance. Multiple laboratory accelerated corrosion tests and on-vehicle service relevant exposures were then conducted on these panel sets. The panels from both types of testing were evaluated for the extent of corrosion, morphology of corrosion, and the composition of the corrosion products. Of the twenty laboratory accelerated corrosion tests evaluated, only two tests were identified that provide reasonable correlation to the on-vehicle service relevant exposure panels. These two tests, ASTM G85-A4 and ASTM G85-A2, are therefore recommended for evaluating cosmetic corrosion on finished aluminum body panels. Both of these accelerated tests provide the correct corrosion morphology when compared to on-vehicle results. The test methods also create corrosion products that are similar to those observed for the on-vehicle exposures, with the exception that ASTM G85-A2 does not have any sulfur in the environment or the corrosion products. Sulfur is often observed in the corrosion products from the on-vehicle exposures and while the exposure in ASTM G85-A4 includes SO_2, use of SO_2 in the laboratory environment is often difficult. As an alternative, ASTM G85-A2 also provides the acidic environment needed to induce the right kind of corrosion on aluminum when compared to on-vehicle panel exposures. It must be noted that due to the variability that is inherent in corrosion testing, a minimum of three samples/panels should be evaluated for every condition being tested to ensure confidence in the result of the testing. It is also important that the test protocols for the accelerated tests are strictly followed.

12.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Purpose:

The goal of the AMD309 project has been to develop or identify a standardized accelerated corrosion test that predicts the cosmetic corrosion field performance of finished aluminum body panels. Many accelerated corrosion tests have been developed for steel substrates but these do not induce the type and/or extent of corrosion on aluminum that is observed in the field. The continued acceleration in the use of aluminum on automotive vehicle bodies requires a cosmetic corrosion test that more accurately predicts field corrosion performance.

Conclusions:

The recommended test methods, ASTM G85-A4 and the ASTM G85-A2, provide relative rankings of corrosion performance that are consistent with on-vehicle exposures. Panels that simulate metal finishing on aluminum prior to paint application consistently exhibited substantially more corrosion than those with standard mill finish in the on-vehicle exposures. For different aluminum alloys processed under standard conditions there was no significant difference in the service relevant on-vehicle performance, with minimal corrosion observed on any of the panels with standard mill surface finish. ASTM G85-A4 and the ASTM G85-A2 are the two laboratory test methods that consistently showed significantly more corrosion on the panels with metal finishing and little or no corrosion on the panels with standard mill finish, thereby providing the correct ranking in terms of the extent of corrosion for the aluminum panel sets. Both of these accelerated tests provide the correct corrosion morphology when compared to on-vehicle results. Both test methods also result in corrosion products that are similar to those observed for the on-vehicle exposures, with the exception that ASTM G85-A2 does not have any sulfur in the environment or in the corrosion products. Sulfur is often observed in the corrosion products from the on-vehicle exposures. The ASTM G85-A4 test includes SO_2 in the environment resulting in incorporation of sulfur in the corrosion products.

12.3 Deliverables/Products Developed

- Recommended test method for predicting the cosmetic corrosion field performance of finished aluminum body panels.

12.4 Technology Transfer Activities

12.4.1 Proprietary Reporting

- DOE Semi-Annual Reports & Offsite Presentations.

12.4.2 Non-Proprietary Publications and Proceedings

[1] Bovard, F. et al., "Development of an Improved Test for Finished Aluminum Autobody Panels," SAE Paper No. 2008-01-1156, SAE 2008, April 2008.

[2] Bovard, F. et al., "Update on the Development of an Improved Test for Finished Aluminum Autobody Panels," SAE Paper No. 2007-01-0417, SAE 2007, April 2007.

[3] Bovard, F. et al., "Development of an Improved Test for Finished Aluminum Autobody Panels," SAE Paper No. 2005-01-0542, SAE 2005 Transactions Journal of Materials and Manufacturing, March 2005.

[4] Courval, G. et al., "Development of an Improved Test for Finished Aluminum Autobody Panels," SAE Paper No. 2003-01-1235, Proceedings of SAE World Congress, March 2003.

[5] Bovard, F. et al., "Update on the Development of an Improved Test for Finished Aluminum Autobody Panels," SAE Paper No. 2009-01-0891, SAE 2009, April 2009.

[6] Bovard, F. et al., "Cosmetic Corrosion Test for Aluminum Autobody Panels: Final Report," SAE Paper No. 2010-01-0726, SAE 2010, April 2010.

[7] DOE Annual Reports.

13. Low-Cost Powder Metallurgy Technology for Particle Reinforced Titanium Automotive Components: Manufacturing Process Feasibility Study (AMD310)

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- ADMA Products, Inc.
- University of Idaho, IMAP

Project Duration: May 2003 – August 2004

13.1 Executive Summary

The concept feasibility study is to develop a simple powder metallurgy manufacturing process to fully densify compacts using novel materials and processing technology.

The USAMP research objective for titanium had 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 noise, vibration and harshness to potentially eliminate the balance shaft system, etc.

A cost competitive manufacturing process with acceptable microstructure/mechanical properties is the benchmark set for the project to reach as the decision gate for connection rod application in high-performance engines.

This involves the addition of reinforcement to stiffen the titanium matrix. It used various titanium metal powders blended with particulate materials as reinforcement in conjunction with powder metallurgy press-and-sinter technology to manufacture simple parts for evaluation.

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 titanium alloys reaching the fully densified state in simple geometry. The whole operation, using blended elemental powders and simple press-and-sinter powder metallurgy operation, was carried out in a cost-effective manner.

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

13.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project goal was to produce Ti-6Al-4V alloys, with and without reinforcing particles, consolidating to a porosity-free state by powder metallurgy technology and meeting the target properties set by the team in a cost-effective manner.

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.

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

The study demonstrated green compacts, with or without reinforcement, could be fully densified upon sintering via the press-and-sinter powder metallurgy approach. The program yielded fully dense titanium metal matrix composites consisting of Ti-6Al-4V alloy reinforced with carbide particles. Reinforcement improved modulus of elasticity as much as 20%. The developed process was claimed to be cost competitive for the automotive industry.

13.3 Deliverables/Products Developed

- Press and sinter material/process database for green compacts of titanium MMC.

13.4 Technology Transfer Activities

13.4.1 Proprietary Reporting

- DOE Semi-Annual Reports & Offsite.
- Manufacture of Cost-Effective Titanium Powder from Magnesium Reduced Sponge, No. U.S. 6,638,336 B1, October 28, 2003.
- Fully-Dense Discontinuously-Reinforced Titanium Matrix Composites and Method for Manufacturing the Same, Filed on 12/29/2003, Application # 10/748,619.
- Method of Titanium Powder Production, Ukrainian Patent #51917 A, December 16, 2002.

13.4.2 Non-Proprietary Publications and Proceedings

[1] Froes, F.H. (Sam) et al., “Titanium Powder Metallurgy – Automotive and More,” 2004 International Conference on Powder Metallurgy & Particulate Materials, Chicago, IL, Part 7, pp. 178-188, June 13-17, 2004.

[2] Froes, F.H. (Sam) et al., “The Technologies of Titanium Powder Metallurgy, *JOM*, pp. 46-48, November 2004.

[3] Froes, F.H. (Sam) et al., “Titanium Powder Metallurgy in Aerospace and Automotive Components,” 2003 International Conference on Powder Metallurgy and Particulate Materials,” Mandalay Bay – Las Vegas, June 8-12, 2003.

[4] Moxson, V.S. et al., “Optimizing Fatigue Performance in Titanium Automotive Components,” 2003 International Conference on Automotive Fatigue Design & Applications, Novi, MI, October 28-29, 2003.

[5] Moxson, V. S. et al., “Ti-6Al-4V Properties Achieved via Extra Low Chlorine Titanium Powder,” *Non-Ferrous Materials Advances in Powder Metallurgy and Particulate Material*, Vol. 6, pp. 125-140, 1992.

[6] Moxson, V.S. et al., “Production and Application of Low-Cost Titanium Powder Products,” *International Journal of Powder Metallurgy*, Vol. 34, (5), pp. 45-53, 1998.

[7] DOE Annual Report.

14. Springback Compensation Project for Advanced Sheet Forming Materials (AMD311)

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- National Institute of Standards and Technology (NIST)
- ThyssenKrupp-Budd
- US Steel (USS)
- Technologies Research Corporation (TRC) of NCMS

Project Duration: January 2003 – December 2003

14.1 Executive Summary

The goal of the Springback Compensation project was to develop and validate a software package that would enable computer-aided engineering analysts to correct for springback encountered in automotive sheet stamping operations. When fully implemented, the software would automatically:

- Analytically predict and recommend.
- Optimized tool geometry (finite element analysis mesh and computer-aided design surface) and the stamping process, which would produce panels with the desired final shape after springback.

In this nine-month concept feasibility project, several promising compensation strategies identified by the original equipment manufacturer-supplier team were evaluated, including direct and iterative methods. Vendor-supplier finite element modeling code was used to conduct numerical simulation tests on representative automotive panel geometries. The numerical results showed minimized deviation from nominal for automotive parts using the newly developed compensation package. Further development and validation are required to evaluate the compensation strategies and associated software modules on a greater variety of components and advanced sheet materials. This technology is an important enabler to compress die development and try-out costs and time.

14.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The concept feasibility phase of the project was concluded on time and met all stated intermediate milestones and objectives within the budget and schedule. Following are the main accomplishments:

- The team evaluated and implemented new supplier-owned FEM (manual compensa-tion) code, and collaboratively performed iterations to test mesh-based, iterative-based analytic (manual) die compensation techniques and prototype software released by LSTC for porting to common workstations.
- Vendor staff trained and trouble-shot with the Springback Compensation team users to implement and run the prototype Springback Compensation project code on a wide variety of materials and geometries for evaluation within the automotive part design/analysis environment.

- Geometric Compensation Method was developed and a software module delivered by ETA to the project team, with GUI pre-/post-processors implemented in DYNAFORM®. The software was developed exclusively for use by the USAMP team.
- The robustness of the developed compensation strategies was tested manually and compared against production part die faces with numerical data developed by the project team.
- For all parts, the predicted springback at critical measurement locations on the compensated virtual production dies was within specified tolerance of ± 2mm.

14.2.1 Computer Modeling Work

Geometric Compensation Method was developed and a software module delivered by ETA to the project team, with graphical user interface (GUI) pre-/post-processors implemented in DYNAFORM®. The modeling software was developed exclusively for use by the USAMP team.

14.3 Deliverables/Products Developed

- Geometric Compensation Method demonstrated.
- Integrated modeling package for prediction of compensated die.

14.4 Technology Transfer Activities

14.4.1 Proprietary Reporting

- Project results were communicated at the Springback Compensation project offsite meetings and to DOE via Semi-Annual Report.

14.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Report.

15. Improved Automotive Suspension Components Cast with B206 Alloy (AMD405)

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- University of Windsor
- Sync Optima Design
- Nemak

Project Duration: October 2004 – Present

15.1 Executive Summary

For suspension applications, aluminum forgings are considered the lightweight baseline whereas ductile iron is the baseline for cost. The goal of this project is to demonstrate that B206 alloy, a high-strength aluminum alloy, can achieve equivalent material properties as aluminum forgings, but at lower costs than forgings. This would enable the project objective of providing a lightweight alternative to more commonly selected ferrous materials for automotive suspension applications. This project successfully demonstrated the technical feasibility of using the B206 alloy for automotive suspension applications by casting a currently forged original equipment manufacturer aluminum control arm design with equivalent material properties and performance as the forged aluminum control arm.

Prior to casting control arms, significant work was done to determine the optimum chemistry and heat treatment that would meet or exceed the forged aluminum control arm mechanical properties. A study of tensile properties versus alloy composition was conducted by researchers at Rio Tinto Alcan using separately cast ASTM B108, permanent mold test bars. A second study was completed by Nemak at their Central Development and Technology Center in Mexico. The results showed that the strength and elongation of the material are sensitive to freezing rate, and rapid solidification is necessary for best properties. The results of this work were compiled into a set of casting and design guidelines for foundrymen who want to pour 206 alloy.

Another important output from this work was a recommendation for a new version of the 206 alloy. Accordingly, new composition limits were proposed for a “C” version of the 206 alloy which should be less expensive to produce than the current B206 alloy.

An extensive experimental program was undertaken at the University of Windsor in Ontario, Canada; with assistance from the laboratories of Rio Tinto Alcan. The program consisted of three primary tasks: (1) determine the effect of aging on mechanical properties, (2) measurements of stress corrosion resistance, and (3) evaluate alternative T7 treatments.

A simple cost model was constructed, which compared the relative costs of suspension components cast in A356 and B206 alloys.

An original equipment manufacturer forged 6082-T6 aluminum production control arm was selected as the target application for comparison using four casting processes:

- Sand mold
- Semi-permanent mold
- Ablation mold

- Tilt-pour permanent mold.

In summary, this project identified optimum combinations of alloy composition, casting process and heat treatment for the B206 alloy; and demonstrated that alloy suspension components can be produced commercially in this material. The resulting suspension components may offer cost savings when compared to A356-T6 or 6082-T6 alloys. There is one caveat, however. The heat treatment and thermal history of 206 alloy must be controlled to avoid sensitivity to stress corrosion. Suitable heat treatments were identified in this project, together with test procedures that may be used to establish that the desired immunity to stress corrosion cracking has been produced.

15.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Phase I – Determine the effect of alloy composition on casting material properties in T4 and T7 tempers, and establish the feasibility of using less expensive versions of the alloy.

A study of tensile properties versus alloy composition was first conducted by researchers at Rio Tinto Alcan using separately cast ASTM B108, permanent mold test bars. These results showed that best mechanical properties are obtained with two separate alloy compositions, depending on whether the T7 or the T4 temper is used. These two alloy compositions are:

<u>T4 Temper</u> – The alloy should contain 4.7 to 4.9% Cu, 0.35% Mg and 0.2% Mn. The expected tensile properties are 250-260 MPa yield strength, 430-450 MPa ultimate tensile strength, and 17-22% elongation. The maximum recommended copper in this alloy is 4.9%, since larger amounts may not go into solution during a standard heat treatment.

<u>T7 Temper</u> – For a ductile T7 casting, the alloy should contain 4.2 to 4.4% Cu, 0.15% Mg, 0.2% Mn, <0.10% Fe and <0.10% Si. The expected average tensile properties would be: 360-390 MPa yield strength, 445-455 MPa ultimate tensile strength, and 6 to 9% elongation.

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

A second stage of Phase I casting trials was also completed by Nemak researchers at their Central Development and Technology Center near Monterrey, Mexico. Twenty 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. A number of important observations may be drawn from the Nemak study:

- The hot crack resistance does not vary significantly over the composition range of the alloy.
- As expected, the propensity for hot crack formation was much less in sand molds.
- Zinc additions have no beneficial effect in this alloy. On the contrary, a small loss of strength was noted when significant amounts of zinc were present. For this reason, the recommended maximum limit of zinc in B206 alloy is 0.05%.
- The best combination of mechanical properties was obtained when B206 alloy castings were heat treated to the T4 temper. In this condition the most rapidly solidified sections of the casting had 15-21% elongation, a yield strength of 220-280 MPa and an ultimate tensile strength of 370-450 MPa. The highest strengths were found at the higher range of alloy compositions.
- It would be useful to increase the maximum limit for magnesium from 0.35-

0.55%. This would allow for an increase of 30 MPa in the yield strength of B206 alloy in the T4 temper.

- As expected, the elongation and ultimate tensile strength of the material are sensitive to freezing rate. Rapid solidification is necessary for best properties. Castings heat treated to the T4 temper have a reasonable tolerance for the impurity elements iron and silicon. Depending on the desired elongation and the freezing rates in a casting, the maximum allowable limits for these elements can be increased. Accordingly, new composition limits were proposed for a "C" version of 206 alloy.
- Metallographic examination of B206-T7 castings showed that a significant amount of Al-Cu-Mn-Fe phase precipitates at grain boundaries. It would be worth exploring different solution heat treatments, to see if it is possible to dissolve this phase. Alternatively, one might lower the manganese content in the alloy. It is possible that elongations in the T7 temper could be increased in this way.

Judging from the mechanical property data, it appears the iron to silicon ratio of the alloy may be important for B206-T7 castings. Further study would be required to establish if this is, in fact, the case.

Phase II – Study heat treatment and stress corrosion, and provide improved T7 heat treatment cycles to increase elongation in the T7 temper.

An extensive experimental program was undertaken at the University of Windsor in Ontario, Canada; with assistance from the laboratories of Rio Tinto Alcan. The program consisted of three primary tasks:

1. *Effect of aging on mechanical properties*—The heat treatment of B206 alloy was studied in detail. The alloy conductivity, hardness and tensile properties were determined as a function of aging time and temperature. Limited studies were also performed on solution heat treatment, even though this work was not part of the original Statement of Work.

2. *Measurement of stress corrosion*—Measurements of the B206 alloy resistance to corrosion and stress corrosion cracking were made by two techniques. The first was the test for grain boundary attack outlined in ASTM G110. The second was the 30-day alternate immersion test as described in ASTM G44. There is a good correlation between the two tests. However, the grain boundary attack procedure is not sufficiently accurate or reliable to replace the alternate immersion technique for qualification tests.

3. *Alternative T7 treatments*—A number of alternative aging cycles were examined to improve the mechanical properties obtained for B206 alloy in the T7 temper. Two alternative heat treatments were identified as possible candidates, but the long aging times required made them cost prohibitive. Retrogression and reaging (RRA) techniques have been used successfully to improve mechanical properties in overaged (T7) Al-Zn-Mg alloys. Unfortunately, the aging mechanisms in B206 alloy (Al-Cu-Mg alloy system) are sufficiently different so that RRA techniques do not work in this material.

Phase III – Provide cost models for cast control arms, to establish the relative cost of B206 alloy suspension components.

Cost models are difficult to construct, since actual costs of piece parts are dependent on many factors, which can change with time. Similarly, subtle differences in a product's design can favor one process or material over another. Even the selection of suppliers can influence the pricing when the manufacturing process is the same. And finally, actual production costs are difficult to obtain, since most companies consider their internal cost structure to be proprietary.

In light of the above issues, and the limited resources available for this phase of AMD405, a simplified approach was taken. The intention was to answer the most basic commercial question: "Can automobile suspension control arms made of cast B206 aluminum alloy be competitive in the market place?" To answer this question a cost model was constructed to compare the differences between material and casting costs for the two aluminum alloys: B206 (in both the T4 and T7 tempers) and A356 (in the T6 temper). Since A356-T6 alloy control arms and knuckles are now being manufactured in reasonable quantities, the cost of these parts represent a "calibration point" for the Phase III cost model.

The actual cost model is an EXCEL spreadsheet. An example calculation using the model is shown in Table 15-1.

This calculation was made for the GM control arm serving as the "mule" casting in AMD 405.

The material (alloy) cost was based on prevailing prices at the time (early 2006). The casting weight was estimated from load criteria

Table 15-1. Cost Model

Cost Comparison
206-T4, 206-T7 and 356-T6 Alloys

	356-T6	206-T4	206-T7
Mat'l Cost $/kg	2.00	2.20	2.20
Casting Weight, kg	4.89	4.57	3.9
Engr'd Scrap, kg	2.10	2.23	1.90
Melting & Handling, $/kg	0.5	0.5	0.5
Amortized Equipment, $/kg	0.00	0.00	0.00
Casting Oper. $/casting	9.78	10.05	8.58
Production Scrap, M/S	1.15	1.17	1.17
Solution Heat Treat, $/kg-hr	0.0110	0.0110	0.0110
Solution Heat Treat, hrs	6.00	10.00	10.00
Aging Heat Treat, $/kg-hr	0.0044	0.0044	0.0044
Aging Heat Treat, hrs	8.00	0.00	4.00
Cost of Heat Treatment, $/part	0.4949	0.5027	0.4976
Value of mass savings, $/kg	0.00	0.00	0.00
Base Cost, $/casting	15.6119	16.03865	13.72519
Difference		-0.42675	1.886711

supplied by GM and stress analyses conducted by Sync Optima Design. Other cost factors were either estimated from data supplied by commercial foundries or represent standard operating practices. The last item, the value of mass savings, represents the cost saving associated with lighter weight of an automobile. Undoubtedly there is some saving, but it has been assigned the value of zero for this calculation.

For the example shown above the B206 alloy in the T7 temper has the potential for significant cost reductions compared to A356 alloy castings, even when the market price of the B206 alloy is 10% more and when both casting designs are fully mass optimized. The reason for the cost saving is that the higher yield strength allows for the use of less material. For the assumptions shown in the model, the cost savings would be $1.89 per casting when using the B206 alloy in the T7 temper. However the 206 alloy in the T4 temper shows a small cost disadvantage of $0.43 per casting. This is because the yield strength of the B206-T4 material is less, and so the weight saving is smaller, and not large enough to offset higher unit costs compared to A356 alloy.

The white boxes in Table 15-1 represent data entries entered by the user. Thus, it will be easy to make additional calculations for other conditions, adding to the utility of the cost model.

The above example calculation suggests that B206 alloy components will not be cost competitive in the T4 temper. However, this calculation was made early in this project and does not incorporate more recent findings. In particular:

1. The yield strength in the T4 temper can be raised about 30 MPa, or 10%, by increasing the maximum allowable magnesium from 0.35-0.55%. This change would reduce the total component weight in this example to

about 4.40 kg. This reduces the cost by $0.374.

2. The "C" version of 206 alloy can be used in the T4 temper. This will be less costly (compared to B206 alloy) by about $0.13 per kg. This reduces the cost of the component by another $0.572.

3. The above two cost reductions add up to a total of $0.946, and make the cost of C206-T4 components equal to $15.0905, a saving of $0.5214 compared to A356-T6 control arms. But there may also be an additional factor to consider.

4. For a given applied stress, the fatigue life of B206-T4 components is nearly 10 times better than A356-T6 alloy. It is also almost twice that of B206-T7 alloy components. (See results of the Phase IV study.) Thus, additional savings may be possible when the design of B/C206-T4 alloy components are determined and limited by fatigue failure.

Phase IV – Produce B206 "mule" castings by a semi-permanent mold casting process and a second casting process; complete mechanical property testing in T4 and T7 tempers and establish engineering capability of B206 suspension parts.

During this phase of work castings, based upon an original equipment manufacturer forged aluminum design, were produced to verify experimental findings during this project and the prior AMD305 project. Initial work at Nemak during Phase I and Phase II of this project resulted in decisions to have control arms cast from semi-permanent mold (Morel Industries) and Ablation (Alotech), since both processes were believed to have sufficient cooling rates to achieve the target mechanical properties of the baseline forged control arm. Control arms from both processes were heat treated to the T4 and T7 tempers. Mechanical properties were measured for all four conditions (casting process and heat treatment) but semi-permanent mold – T7 control arms (labeled PT7) were pre-selected for bench test fatigue testing.

Seven PT7 castings were machined and bushings and a ball joint were press fit into the control arms. The assembly was mounted on a full-scale test bench and stressed under cyclic load until fatigue failure occurred. The failure location was the same for all castings and the same as the base-line forged control arms. The castings gave a performance nearly equal to, but slightly less than the forged control arms. However, these tests were made on PT7 castings, which had the lowest fatigue strength of all castings produced. Better performance results would have been expected had the project bench test used castings in the T4 temper.

In summary, the results of this phase of study indicate that:

- The B206 alloy can produce equivalent mechanical properties as forged aluminum.
- Bench tests indicate that B206 will also be competitive with forged aluminum with respect to component fatigue performance.

The results of this phase also show that the heat treatment and thermal history of 206 alloy must be controlled carefully to avoid sensitivity to stress corrosion. Suitable heat treatments were identified, together with test procedures that may be used to establish that the desired immunity to stress corrosion cracking is present.

15.3 Deliverables/Products Developed

- Various control arms
- Test procedures
- Cost model
- Heat treatment database.

15.4 Technology Transfer Activities

15.4.1 Proprietary Reporting

- DOE Semi-Annual Reports and Offsite Slides.

15.4.2 Non-Proprietary Publications and Proceedings

[1] Sigworth, G.K. et al., "Use of High Strength Aluminum Casting Alloys in Automotive Applications," Light Metals 2001 Métaux Léger, eds. M. Sahoo and T.J. Lewis, Canadian Inst. Mining, Metallurgy and Petroleum, Montreal, Quebec, pp. 313-322, 2001.

[2] Sigworth, G.K. and DeHart, F., "Recent Developments in the High Strength Aluminum-Copper Casting Alloy A206," AFS Transactions 2003, Vol. 111, pp. 341-354, 2003.

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[4] Sigworth, G.K. and Major, J.F., "Factors Influencing the Mechanical Properties of B206 Alloy Castings," *Light Metals 2006*, pp. 795-800, 2006.

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[7] Rodríguez, A. et al., "The Effect of Solidification Conditions and Alloy Composition on the Castability and Mechanical Properties of B206 Alloy," *Trans. American Foundry Society*, Vol. 117, pp. 79-92, 2009.

[8] Jean, D. and Major, J.F., "Chemistry/Property Relationships in AA 206 Alloys: Fatigue Behavior," *Trans. American Foundry Society*, Vol. 117, pp. 103-112, 2009.

[9] Jean, D. et al., "Heat Treatment and Corrosion Resistance of B206 Aluminum Alloy," *Trans. American Foundry Society*, Vol. 117, pp. 113-120, 2009.

[10] DOE Annual Reports.

16. Ultra Large Castings for Lightweight Vehicle Structures (AMD406)

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- COSMA International/Promatek Research Centre
- Creative Concepts Company

Project Duration: July 2006 – August 2009

16.1 Executive Summary

The Ultra Large Casting (ULC) project builds on previous work to assess manufacturing feasibility, economics and mass reduction potential of thin-wall structural castings of aluminum and magnesium applied to automotive weight reduction.

A case study of an existing ULC application, the Ford F-150 magnesium radiator support, is used to substantiate the rationale for substituting large castings in place of multi-piece stamped steel welded assemblies by validating the assumption that large castings reduce cost through functional integration of components and reduce weight by lower material density and elimination of structural redundancies. The case study of the Ford F-150 cast magnesium radiator support validates the assumption that designs based on ULCs have excellent potential to significantly reduce weight and cost versus the conventional stamped steel designs.

Expanding the use of large automotive primary structural castings is limited by the process capabilities and inherently inconsistent mechanical properties achievable with conventional high-pressure die-casting (HPDC), which is the industry's preferred high-volume manufacturing process for large castings. Although it is familiar and simple, the nature of the HPDC process, equipment and practices results in castings with high levels of porosity. This porosity, the levels of which can be unpredictable, negatively impacts mechanical properties. The few large structural castings (F-150 magnesium radiator support/Dodge Viper dash structure) and quasi-structural castings (side door and liftgate inner structures/instrument panel cross car beams) are manufactured with the HPDC process, and while they perform adequately, HPDCs may not be suitable for other primary structures like pillars, rails or body sides that require a certain level of ductility to manage large amounts of crash energy.

An alternative to HPDC processes is semi-solid forming (SSF). This project addressed in detail the viability of sub-liquidus casting (SLC) and thixomolding since they are deemed to have the potential for demonstrating improved mechanical properties utilizing existing equipment of a reasonable size (e.g. 1,000 ton machines). The thixomolding effort, which is used only for casting magnesium, includes a demonstration and evaluation of an industry-first asymmetrical multiple hot-runner direct injection system. The SLC effort focused on a "test part" geometry specifically designed to evaluate the process for production of ULCs and is used to cast aluminum and magnesium demonstrating direct gating into the die cavity.

The demonstration chosen by the ULC team was to replace the conventional multi-piece steel structure that formed the F-150 inner front fender – known in the industry as a "shotgun" with a single casting. While this particular component would not necessarily be considered "ultra large," it embodies the geometric elements and manufacturing challenges that would be encountered in a much larger component, such as an entire body side. The F-150 shotgun application was of further interest because it is integrated into the body structure where it contributed to stiffness (which has durability and noise, vibration and harshness implications) and played a role in conducting and absorbing crash energy. The end result of Phase II was an integrated front-end structure for a large body-on-frame pickup or SUV constructed entirely of magnesium castings demonstrating a weight savings of 67% compared to conventional steel architectures and a savings of 45% compared to the baseline. The finite element analysis simulations predict that the cast magnesium design will perform better than the stamped steel design in static durability. Physical testing confirms this prediction. The fatigue test, which is the most relevant test, shows that the cast magnesium shotguns performed equal or better than the stamped steel shotguns at about half the weight.

16.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

1. *Establish a rationale for using large light metal castings in place of conventional multi-piece stamped and welded steel automotive body structures to enable lightweight vehicle structures and systems that meet the Technology-Specific Research Goals for "Materials" as stated in the FreedomCAR and Fuel Partnership Materials Technology Roadmap.1 (50% mass reduction/affordable/recyclable)*—A case study of an existing ULC application was used to substantiate the rationale for substituting large castings in place of multi-piece stamped steel welded assemblies by validating the assumption that large castings reduce cost through functional integration of components and reduce weight by lower material density and elimination of structural redundancies.

2. *Evaluate alternative manufacturing processes to the HPDC process for their potential to enable the production of aluminum and magnesium primary automotive cast structural components with consistent and predictable mechanical properties*—This project addresses in detail the viability of SLC (for aluminum and magnesium) and thixomolding (for magnesium) for their capability to produce parts with features required for ULCs.

<u>SLC</u>

- Developed test part geometries.
- Developed re-configurable test part tooling.
- Measured fluidity characteristics of aluminum and magnesium at various thicknesses and different process parameters.
- Analyzed mechanical property data of thin-walled SLC cast aluminum and magnesium.
- Conducted visual and x-ray quality assessment of typical thin-walled aluminum and magnesium structural shapes cast with SLC.
- Determined SLC had low potential for producing castings having the desired improvements to mechanical properties required for large, thin-walled primary structural ULCs.

<u>Thixomolding</u>

- Industry-first use of an asymmetrical 4-drop hot runner system.
- Conducted designs of experiments to determine optimum process settings.
- Established a statistically significant benchmark for HPDC magnesium tensile

properties to compare to thixomolded magnesium "shotgun" tensile properties.

- Achieved 60% better elongation vs. benchmark HPDC (9.05% vs. 5.68%)
- Achieved 20% better ultimate strength and 9% better yield strength (238 MPa and 134 MPa)) compared to benchmark HPDC (197 MPa and 123 MPa).
- Determined that thixomolding with hot runners has good potential to produce castings having the desired improvements to mechanical properties required for large, thin-walled primary structural ULCs.

3. *Demonstrate a "read world" application of a cast primary automotive structural component which embodies the geometric elements and manufacturing challenges that would be encountered in a much larger casting—*

- Cost study of magnesium shotgun.
- Integrated shotgun into an all-magnesium ULC front-end structure.
- Fabricated three body-in-whites with all-magnesium ULC front-end for testing.
- Performed design verification component testing of shotgun.
- Performed design verification and system level testing of all-magnesium ULC front-end structure.
- An integrated front-end structure for a large body-on-frame pickup or SUV constructed entirely of magnesium castings demonstrating a 66% weight savings compared to conventional steel architectures and a 45% weight savings compared to the baseline design.

16.3 Deliverables/Products Developed

- Test part geometry for demonstration parts.
- Tooling systems for semi-solid and thixomolding processes.
- Materials analysis reports and performance data.

16.4 Technology Transfer Activities

16.4.1 Proprietary Reporting

- Various AMD Offsite talks and DOE Semi-Annual Reports.
- A comprehensive report titled, "An Engineering Study into Required Performance of, and Conceptual Design Solutions for a High Productivity Casting Process for Making Large Thin Castings in Aluminum and Magnesium."

16.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

17. Die-Cast Net-Shaped Hole Process Development (AMD407)

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Team Members:

- ATF
- EJOT
- REMINC
- Textron Fastening Systems
- General Motors Corporation
- DaimlerChrysler Corporation
- Ford Motor Company
- Visteon
- Mercury Marine
- Atlas Copco
- Rexroth Bosch

Project Duration: January 2005 – February 2007

17.1 Executive Summary

The focus of this technical feasibility project was resolving the highest priority technical challenges associated with application of thread-forming fasteners (TFFs) into die-cast, net-shaped holes in aluminum and magnesium alloys identified during the initial concept feasibility project completed in 2003. Those priority issues were grouped into four technical challenges: (1) casting variation, (2) fastener design, (3) assembly processing and (4) in-service requirements. The major facets of casting variation are cast hole size, shape and position resulting from the thermal, mechanical and metallurgical effects of the die-casting process. Fastener testing was conducted to evaluate the effect of hole size and shape on clamp load. The closely related in-service issues of contamination and reusability were also evaluated via fastener testing. In addition, in-field data was collected from casting suppliers on die pin wear and degradation. A variety of fastener designs provided by fastener suppliers and assembly procedures were used to evaluate the extent to which TFFs could be employed in die-cast net-shaped holes in lightweight alloys. All of these prioritized issues were addressed for both aluminum alloy A380 and magnesium alloy AZ91D during this Phase I technical feasibility project.

This technical feasibility project has aimed to resolve the highest priority issues associated with applying thread-forming fasteners in die-cast net-shaped holes in lightweight alloy castings. The combination of fastener testing results and in-field casting variation measurements can be coupled together to conclude that indeed capability exists to use thread-forming fasteners in as-cast components currently in production today. This capability was assessed using a variety of fastener designs in both aluminum and magnesium die-casting alloys and by assessing the variation in components produced by multiple casting suppliers.

17.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

1. *Hole size and shape laboratory fastener testing*—Several M6 fastener designs were tested in each material to demonstrate that the capability to use die-cast net shaped holes could be accomplished by multiple fastener designs. It is important to note that the testing was designed and executed for casting variation analyses and not for fastener performance or comparison. No attempt was made to optimize the tests or castings for fastener performance. All of the fasteners performed satisfactorily during the tests.

2. *Reusability testing*—The purpose of the reusability test was to evaluate the capability for a fastener to maintain clamp load after

repeated installation of the same fastener into the same hole. To achieve this, the clamp load at a target input torque was measured for 14 consecutive rundowns of a single fastener into a die-cast nut specimen. For a given fastener design, the target input torque was experimentally determined to be the torque required to generate 9 kN of clamp load. This clamp load target was also established experimentally as the load generated by installing a machine screw at 11 Nm of input torque which is a common assembly specification range (10-12 Nm) for M6 fasteners. After 14 consecutive rundowns, the torque limit was removed and the fastener tested to failure. Clamp load and input torque at failure as well as the failure mode were recorded to conclude the test.

3. *Contamination testing*—Another technical feasibility issue to be investigated during this project was to determine the extent to which contamination in the form of debris was generated while using TFFs in aluminum and magnesium alloy die-cast, net-shaped holes. The approach to this test was to collect and weigh any debris generated during installation of the fastener during the reusability tests. Debris was cumulatively weighed using an electronic balance after the 1^{st}, 2^{nd}, and 5^{th} rundowns of the reusability sequence. Samples of collected debris were then analyzed using a scanning electron microscope equipped with an energy-dispersive spectrometry detector to determine the composition of the debris collected.

4. *In-field casting variation evaluation*—Instead of measuring actual cast holes, the approach selected was to measure the core pins that made the holes. Core pins were measured before dies were put back into service from major maintenance overhauls. Most dies are taken out of service every 20,000 to 40,000 cycles for routine maintenance and core pin replacement. The same core pins were removed and measured after the dies were removed from service for the next major maintenance overhaul. Three typical automotive casting dies used for aluminum components were included in the study, ranging in size from a pump body casting to a transfer case casting to a transmission case casting.

17.3 Deliverables/Products Developed

- Test performance data on M6 fasteners incorporated in Al 380 and AZ91D materials.

17.4 Technology Transfer Activities

17.4.1 Proprietary Reporting

- AMD Offsite Presentations and DOE Semi-Annual Reports.

17.4.2 Non-Proprietary Publications and Proceedings

[1] Paxton, D.M. et al., “Application of Thread-Forming Fasteners in Net-Shaped Cast Holes in Lightweight Metal Alloys,” The Minerals, Metals & Materials Society (TMS) Letters: Lightweight Materials, 2006.

[2] Paxton, D.M. et al., “Application of Thread-Forming Fasteners in Net-Shaped Cast Holes in Lightweight Metal Alloys,” TMS Symposium on Lightweight Materials, March 16, 2006.

[3] Paxton, D.M. et al., “Use of Thread-Forming Fasteners in Lightweight Alloy Die-Cast Net-Shaped Holes,” THERMEC 2006: International Conference on Processing & Manufacturing of Advanced Materials, July 3-6, 2006.

[4] DOE Annual Reports.

18. Die Face Engineering (AMD408)

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Team Members:

- Ford Motor Company
- General Motors Corporation
- DaimlerChrysler Corporation
- U.S. Steel
- Alcoa
- Volvo (division of Ford Motor Company)
- Technologies Research Corporation (TRC)
- Livermore Software Technology Corporation
- U.S. Steel
- Thyssen-Krupp Budd

Project Duration: April 2004 – December 2007

18.1 Executive Summary

Much progress has been made in recent years in predictive simulation of springback for closure parts made from sheet metals such as aluminum alloys and conventional steels. Increasing demands for fuel economy and safety have accelerated the use of lightweighting materials such as advanced aluminum alloys and Advanced High-Strength Steels (AHSS) for stamped automotive components. However, due to their high-strength-to-density ratios and unique microstructures, they pose particular challenges to obtain consistent and accurate dimensional parts, resulting in lengthy and costly die try-out. These materials are often difficult to accurately simulate. The economical use of these materials necessitates the development of advanced simulation-based virtual engineering technology to predict and resolve springback.

The overall objective of the Die Face Engineering (DFE) project was to develop advanced computer simulation and demonstrate compensation technology to dramatically improve virtual engineering capability for emerging lightweighting sheet materials.

The DFE project focused on improving springback prediction accuracy (targeting greater than 90% prediction accuracy for closures), and specifically at modeling the more challenging part designs, newer lightweighting sheet materials such as AHSS and aluminum, while recommending optimized tooling geometry to reduce die try-out effort.

As a result of the DFE project, the tool prototyping steps could be completely eliminated, and die try-out time and cost may be significantly reduced for structural parts fabricated with these newer lightweighting materials. The resulting integrated simulation and compensation technology is expected to more reliably achieve specified dimensional tolerances for stamped automotive parts made from AHSS and aluminum alloys.

18.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The team identified technology gaps, proposed solutions and methodologies, selected and evaluated commercially viable solutions. Five project sub-teams were tasked to address critical industry needs in:

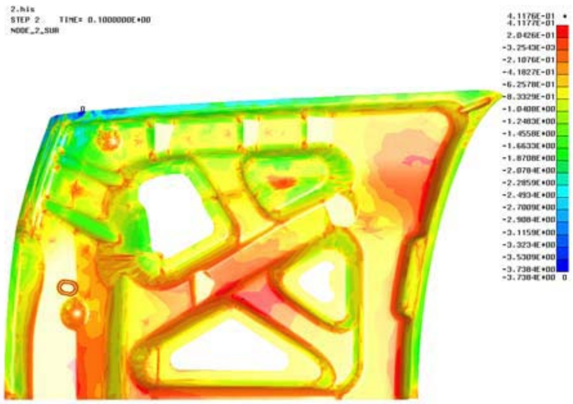
1. *Numerical technology for springback prediction*—The Numerical Team identified known and potential limitations in finite element technology that affect the reliability of springback. This information was shared with LSTC, developers of the LS-DYNA® code which was previously found to perform well in springback prediction of other less complex stampings. LSTC then developed and implemented solutions to address these

identified limitations in the LS-DYNA® code or its supporting pre- and post-processors. The Numerical Team then coordinated the evaluation of these solutions, first for robustness and then for their effect on springback. In some cases these solutions were found to play a minor or negligible role in springback in the “Common Rail Die,” but in other cases, they were found to play a significant role. These studies helped the Numerical Team develop an improved strategy for more reliable springback prediction.

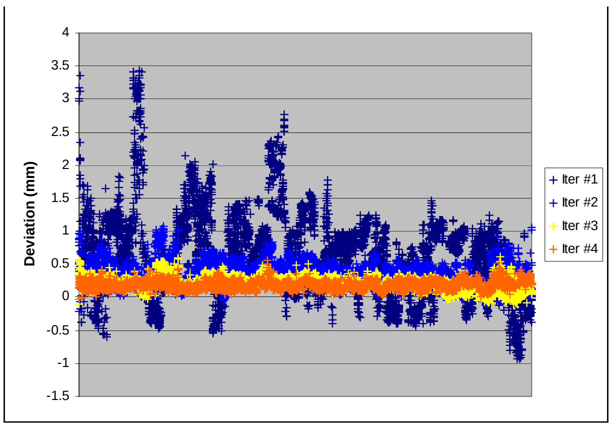
Figure 18-1 shows the example of a hood inner, showing deviation from design intent and how numerical compensation is typically an iterative process. Key DFE accomplishments were:

- Demonstrated baseline springback predictability at critical measurement locations on the Common Rail Die (location, direction and magnitude of springback).
- Demonstrated improved springback predictability at critical measurement locations on the Common Rail Die to within 80% accuracy with Phase II code.
- Demonstrated an improved springback prediction code with improved contact algorithms and through-thickness stress, for various springback characteristics (e.g. twisting, warping and out-of-plane bending).
- Determined feasibility of improved springback prediction with higher order element(s) – after several discussions, the team decided not to pursue this effort due to feasibility issues in production.
- Determined feasibility of surface-based simulation capability for forming and springback prediction – approach was redirected to a more efficient method using smooth contact algorithms.
- Developed and validated new simulation technology for metal forming, including:
  - Smooth contact
  - Normal stress element
  - Selective mass scaling
  - Thick shell element (Element #26)
  - Forming process modeling templates
  - Quasi-static implicit gravity loading
  - MPP-capable implicit/explicit implementations
  - Initial relief of rigid body modes
  - New adaptive mesh algorithm
  - New material models
    - Chaboche model
    - Vegter model
    - Yoshida model with planar isotropy
    - Enhanced Yoshida model with combined power-law/exponential hardening.

2. *Material modeling for improved simulation accuracy*— The team was responsible for identifying candidate models published in the literature, identifying tests and vendors to perform the required material measurements to calibrate these models, coordinating the tests and evaluation of 11 alloys for lightweighting. The team obtained valuable input from the National Institute of Standards and Technology (NIST), LSTC, and several test labs in Europe and Japan for monotonic and cyclic loading under uniaxial and biaxial conditions. An effective model calibration process was developed and data for all alloys were collected and analyzed. Finally, LSTC implemented the candidate models, and the Numerical Team evaluated the models and their calibrations to ensure they were consistent with the experimental test data. Ultimately, the Material and Numerical



(a) Deviation at +4mm at 2nd Iteration



(b) Deviation after Four Iterations

Figure 18-1. Deviations from Design Intent

Teams identified the best candidate model from the literature for springback prediction in the Common Rail Die analysis, and also developed a modification of this model to improve its ability to describe the experimental hardening behavior of steel alloys, which was found to play a significant role in springback prediction. The team:

- Conducted literature review on material models.
- Reviewed reliability of existing material models (yield surfaces, kinematic hardening, etc.).
- Identified and implemented material models in finite element analysis code (Chaboche, Vegter, and Yoshida).
- Identified appropriate vendors for material characterization testing.
- Characterized parameters and validated material models implemented in code for all alloys.
- Generalized Yoshida model for planar anisotropy and with new hardening law to characterize dual-phase (DP) steels.
- Evaluated the new material models for springback prediction using Common Rail Die trial data.
- Developed an extensive material database for advanced constitutive models for 11 metals, including draw quality special killed (DQSK), BH240, high-strength low-alloy (HSLA), DP600, DP780, DP980, TRIP780, AL5754, AL6111, AL6022, and AL5182 alloys, including uniaxial, biaxial, and multi-cycle loadings, as well as failure measurements.
- Documented state-of-the-art material testing methods for large strain cyclic loading and model calibration.

3. *Die surface compensation for springback*—A key goal of the DFE project was to define the requirements for the automotive industry for computer-aided design (CAD) surface morphing technology, and to identify and evaluate existing and emerging commercial software to achieve the objectives. Surface morphing is a challenge in die design because the morphing process tends to magnify discontinuities in the patch surface network that are otherwise acceptable for numerical control (NC) machining of the base surfaces. Due to automation and limited sophistication, the technology may not morph certain 3D surface features in a manner that an experienced die maker would accept. One of the objectives of this project was to inform vendors of this problem and to encourage them to develop *automated solutions* to smooth and fix the morphed

surfaces to consistently meet automotive requirements.

Within the DFE project, a Surface Development Team was formed to: develop the requirements for springback compensation by surface morphing CAD data, identify potential morphing software vendors, and evaluate their technology in view of the requirements on a total of nine automotive component die face surfaces with specified compensation directions. The requirements for surface morphing were refined on the basis of these evaluations. The Surface Development Team:

- Identified surface morphing vendors and developed an evaluation criteria.
- Demonstrated mesh-to-surface and surface-to-surface mapping algorithms with the *same* element topology – Phase I.
- Evaluated current commercial CAD surface morphing packages and established baseline capability.
- Selected vendors for the Phase II study using different elemental topology.
- Conducted Phase II trials for 11 panels using *different* element topology.
- Evaluated NC-ready surface generation algorithms.
- Identified a robust mesh-to-surface and surface-to-surface morphing software package. The identified software has high potential to meet surface quality requirements. With current state-of-the-art, product surfaces still require manual repair of local imperfections.
- Demonstrated NC surface quality of compensated production dies to within ±0.5mm tolerance of the target die surface, while maintaining same surface quality as the original CAD. The DFE project did not consistently achieve target due to an over-reliance on manual methods to repair local imperfections in compensated die surfaces.
- Evaluated existing and emerging commercial CAD surfacing capability for die face compensation.
- Identified gaps in die surface morphing technology for future development.

4. *Industrial experiments for validation of developed technology*—Since springback varies from one product to another, and the success of the project was dependent on accurate springback prediction, a Validation Team was also formed to evaluate the reliability of the springback prediction in an application involving *severe springback issues*, as well as to evaluate the efficacy of the virtual compensation process. This validation included evaluation of all new technological developments necessary to improve springback and/or compensate for springback. The team first focused on springback analysis of a production-sized stamping, based on an existing structural automotive component, a Y-shaped front side rail (Figure 18-2). The shape of the component was then purposefully modified to magnify the severity of the most challenging springback issues, side wall curl and axial twist, and having design features common to all three automotive companies (Figure 18-3). This Common Rail Die became the focal point for early demonstrations of the project's new finite element analysis and CAD advances.

Four sheet metals, DP600, DP780, TRIP780 and AL5754-O, which are identified as candidates for lightweighting automobiles, were stamped in this die to verify springback predictability. In addition to the full-sized product, half-size blanks were also stamped in a section of this same die tool set. Due to significant differences in the boundary conditions for the half-sized blank, large differences in springback were observed. These complementary tests were performed in order to provide an almost-independent

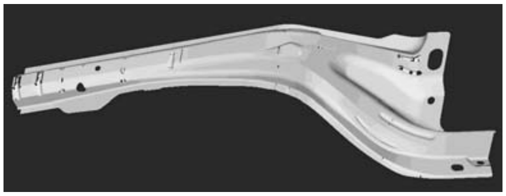


Figure 18-2. Original Shape of the Common Rail Die Product

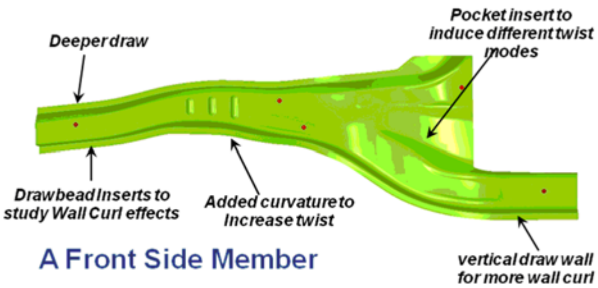


Figure 18-3. Modifications to the Common Rail Die to Increase Severity of Springback Challenge

test of springback predictability, without incurring large additional tooling costs. One of the alloys, DP600, was then selected to verify the compensation technology using the newly developed springback prediction technology from this project. The die surface was then recut based on Tebis' morphing technology and DP600 full-size panels were stamped to verify springback compensation. Results were found to be very good except in a few local areas, where deviations were attributed to errors in the manual repair process to correct for the incomplete automation of the morphing technology. The presence of these errors was an important reminder of why full and robust automation is desired, while at the same time, the confinement of these problems to the limited surface areas where manual correction is required, is a testament to the rapid advances made in automated morphing technology.

In addition to the deliverables for this project, the Validation Team also retained a complete set of surface files for all tooling used in the validation effort, as well as all measurement data from physical tests. These data files are expected to be of significant value to future USAMP efforts to develop, improve, and benchmark new metal forming simulation technology. The team:

- Conducted die face design, engineering, build, try-out, experimentation, and validation for DP600, DP780, TRIP780, and AL5754 on full-scale industrial part including forming, trimming, and springback prediction.
- Generated baseline springback measurement data for both aluminum and using the Common Rail Die.
- Demonstration/validation of springback predictive capability to within 0.5mm in critical locations of the stamped part from the Common Rail Die part with 1.6mm thick DP600 sheet.
- Conducted die face compensation for DP600 based on predicted springback on a full-scale industrial part and validated with stamping try-out.
- Validated LS-DYNA® improvements.

5. *Industrialization process for implementation*—Finally, the business impact was assessed and is documented. This impact includes an original equipment manufacturer estimate of how much cost and time savings are expected from the reduced need for die re-cuts to address springback compensation requirements (that are usually not identified until physical try-out) as well as the percentage of dies that are compensated based on springback prediction prior to and as a result of the DFE project. This Industrialization team:
   - Developed CAD surface quality criteria for die face compensation.
   - Documented impact of new technology in die construction.
   - Developed strategy and procedures for industry implementation for accurate numerical simulation of springback,

including material model selection, element type, contact algorithm, and optimal simulation parameters.

- Integrated forming, springback, and morphing software for industrial application and demonstrated seamless integration of gravity loading, forming, trimming, and springback prediction.
- Generated technical progress and final reports.

Conclusion:

The initial impact from application of the resulting technology compared to the 2004 baseline technology is estimated as follows:

- 30% improvement in the confidence level of virtual prediction of springback.
- 60% increase in applications of springback analysis to predict dimensional quality.
- 75% increase in applications of virtual die compensation based on predicted springback.
- 50% reduction in the die recuts due to springback.

The project's greatly improved predictive capabilities have been expanded to address forming of more challenging automotive parts incorporating lightweighting materials.

18.2.1 Computer Modeling Work

AMD408 validated new LY-DYNA® simulation technology for metal forming, including:

- Smooth contact
- Normal stress element
- Selective mass scaling
- Thick shell element (Element #26)
- Forming process modeling templates
- Quasi-static implicit gravity loading
- Massive parallel processing (MPP)-capable implicit/explicit implementations
- Initial relief of rigid body modes
- New adaptive mesh algorithm
- New material models
  - Chaboche model
  - Vegter model
  - Yoshida model with planar isotropy
  - Enhanced Yoshida model with combined power-law/exponential hardening.

18.3 Deliverables/Products Developed

- Modified Common Rail Die with tooling and data on comparison to uncompensated surface.
- Extensive Material Database on formability.
- New die compensation algorithms.

18.4 Technology Transfer Activities

The automotive company stamping groups and material supplier representatives of the team were directly involved with their respective company's virtual manufacturing simulation activity, and therefore, the knowledge transfer and implementation of the new DFE project technology is implicit in these organizations. Implementation efforts were augmented by the following activities.

18.4.1 Proprietary Reporting

- The DFE project team provided periodic updates to the Department of Energy (DOE), USCAR and USAMP organizations including written reports and offsite presentations.

- Reports and presentations have also been used by team members to communicate progress within their own organizations.
- Training for the new simulation technology provided by LSTC will be integrated with LSTC's ongoing training and support service provided to the automotive industry to update current and educate new engineers.
- The technological challenges and approaches to their solution that have been identified in this project are sufficiently well documented that other vendors of metal forming simulation and surface morphing software may develop equivalent or improved solutions through their business relationships with the automotive industry.

18.4.2 Non-Proprietary Publications and Proceedings

[1] An oral, non-proprietary presentation was provided by the Project Leader on September 17, 2007 at the ASM Materials Science and Technology Conference held in Detroit, MI.

[2] DOE Annual Reports.

19. NDE Inspection of Resistance Spot Welds in Automotive Structures Using an Ultrasonic Phased Array (AMD409)

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Team Members:

- Ford Motor Company
- General Motors Corporation
- DaimlerChrysler Corporation
- Lawrence Berkeley National Laboratory
- National Center for Manufacturing Sciences

Project Duration: July 2004 – March 2007

19.1 Executive Summary

Developing a portable resistance spot-weld inspection system using state-of-the-art, high-frequency ultrasonic phased-array technology was undertaken. Phased arrays were identified in previous work as the most promising nondestructive technique for spot-weld inspection. These ultrasonic systems are capable of simultaneously imaging the weld interior as well as the top and bottom surface conditions in only a few seconds. As forecast at the outset of the project, the phased-array industry has continued to expand and advance rapidly.

The prototype system developed for the project maximized the use of commercially available hardware, but required both custom hardware and software to meet industry's specifications for portability, ease-of-use, cost, measurement speed and accuracy. The resulting system produces repeatable high-resolution images of typical automotive welds. These images provide feedback on weld shape, voids, cracks and surface indentation. Software was developed that analyzes the data to size welds, map surface indentation, and extract data from the signals that are useful in identifying discrepant welds.

The prototype system performance was extensively evaluated on industry-typical galvanized, low-carbon steel welds. These included two industry-made sets of weld coupons and three production parts. The production parts demonstrated the ability to image the welds on a variety of flanges. On the coupons, extensive metallographic analyses and strength tests were carried out to relate the ultrasonic measurements to the weld microstructure.

On galvanized low-carbon steels, which undergo weld hardening, peel strength and button size are primarily determined by the weld-nugget size, whereas lap-shear strength depends on both the nugget and the heat-affected zone (HAZ). There is a significant HAZ around the weld for these steels, in which there is intimate bonding and high ultrasonic transmission across the faying surface. It is because it includes some or all of the HAZ that the ultrasonic transmission area alone is insufficient for evaluating welds. Ultrasonic evaluation is particularly difficult for small welds and thin-thick stackups, where the HAZ can be large and the nugget very small at the welded interface.

Even under these conditions there is a high statistical correlation between predicted button sizes using ultrasonic variables and measured button sizes obtained via teardown and nugget sizes determined from metallurgical analysis. The ultrasonic sizing capability for minimally acceptable welds is on the order of 1 mm in diameter.

It is expected that ultrasonic phased-array technology will be suitable for inspection of spot welds in aluminum and magnesium, where weld inspection may be more straight-forward than for coated steel. The technology also holds promise for inspection of parts made using other joining methods including friction-stir welds. Phased arrays may also provide a more economical alternative to automated weld location systems than vision systems for high-strength materials with small weld indentations. In addition, the versatility of phased arrays that allows optimization of inspection procedures for specific conditions makes them well suited for inspection of critical welds where their attributes can improve accuracy and reliability.

19.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

To best advance the adoption of lightweight materials while also serving the needs of the auto industry, the project team adopted a development strategy that adds value immediately, minimizes the barriers to incorporating emerging technologies at a later date, and that is as flexible as possible so that it can be used for other purposes and adapted for new applications. The prototype spot-weld inspection system described here integrates the best available ultrasonic phased-array technology with custom hardware and custom signal-processing software that allows the portable system to be used in a laboratory or in a manufacturing plant.

The overall project objective was to develop a cost-effective ultrasonic phased-array system that is sufficiently fast, accurate, and robust in manufacturing environments to be suitable for inspection of spot welds in automotive structures. Another important goal was to make inspections easier to perform and analyze than destructive teardown.

To meet these objectives, the following technical goals were put forth:

1. *Develop a spot-weld inspection system based on state-of-the-art ultrasonic phased-array technology that can be used by operators with minimal training* – Although the project described here was focused on development of a universal spot-weld inspection system, the versatility of phased arrays makes them well suited to specific tactical applications that are easier to implement than global strategic initiatives. Because phased-array probes and inspection strategies can be tailored for particular inspection challenges, they should be considered for inspection of critical welds where their attributes can improve accuracy and reliability.
2. *Develop the hardware and software necessary to allow resistance spot welds to be ultrasonically imaged and automatically assessed in a few seconds* – With respect to signal-processing and analysis software, more than 4,000 ultrasonic signals are successfully measured and analyzed for each weld in a few seconds. The speed could be significantly reduced by programming the processing algorithms in hardware, for example, using field-programmable gate arrays (FPGAs). Measurement and processing time meet industry requirements.
3. *Design and fabricate a fully integrated prototype system that is as lightweight, portable and as ergonomic as possible, that is also rugged enough for use in a production facility and flexible enough to ensure access to welds on complex components* – From the hardware side, the integrated probe and the miniature mechanical scanner incorporated into the prototype unit have performed well, but the robustness of the motorized scanner under rough handling in a plant environment may be an issue. An alternative would be a phased-array probe with the elements arranged in a square matrix, or an annular array of elements, both of which would allow two-dimensional electronic scanning of the weld, eliminating the need for mechanical scanning. The cost of such probes was considered prohibitive at the beginning of the project. However, advances in manufacturing technologies and

a growing market have reduced prices, and further reductions are expected in the future.

4. *Conduct validation experiments to demonstrate the prototype system's ability to characterize welds with sufficient accuracy and repeatability* – Challenges exist where accessibility to welds is limited, and where there is a tendency to over weld. Inaccurate placement of welds creates measurement problems if welds are located at the edge of the joint or in tight corners.

   In general, tighter control of welding processes would greatly benefit ultrasonic inspection. At the same time, ultrasonic inspection can provide valuable feedback to the welding process, not only on weld size, but also on loss of material, surface indentation, weld and indentation shape, and the existence of discontinuities inside the weld nugget. Burnt welds are also easily identified. These data provide information on the state and alignment of the electrodes, the fit-up between parts, and the welding parameters. There is therefore a symbiotic relationship between ultrasonic inspection and the welding process: process feedback derived from the ultrasonic signals that can be used to improve welds also reduces the process variability that poses challenges for ultrasonic inspection, thereby enabling greater use of ultrasonics and more reliable results.

   Understanding the relationship between the weld nugget and the weld button obtained during teardown is of fundamental importance for evaluating ultrasonic results. While it is the weld nugget that is of interest, the cost and time required to section welds means that ultrasonic results are almost always compared to weld buttons. The relationship between the weld button and nugget is not sufficiently quantified, and introduces additional uncertainty in evaluating ultrasonic data.

   In general, there is very good qualitative agreement between the processed ultrasonic images and the weld qualities determined from the physical measurements. Features evident in the buttons and metallographic images, such as misshaped welds, and voids and cracks in the nuggets, are also evident in the ultrasonic images.

From these high-level goals, the technical requirements for the prototype system were specified.

In recognition of the fact that the ultrasonic NDE industry is not driven by the automotive nor the manufacturing sector, another important objective of the project is to provide a commercialization path for ultrasonic phased arrays to bridge the market gap between automotive applications and those in aerospace, nuclear power and medical systems. The key element identified for providing a commercialization path is demonstrating the technical feasibility of inspecting resistance spot welds with existing phased-array technology.

The history of the project is illustrated in Figure 19-1 with pictures of the hardware developed, along with images that are the output of the signal-processing software that was also developed over the course of the project.

19.3 Deliverables/Products Developed

- Spot-weld inspection system based on state-of-the-art ultrasonic phased-array technology.

19.4 Technology Transfer Activities

19.4.1 Proprietary Reporting

- ADM Offsite Presentations and DOE Semi-Annual Progress Reports.

19.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

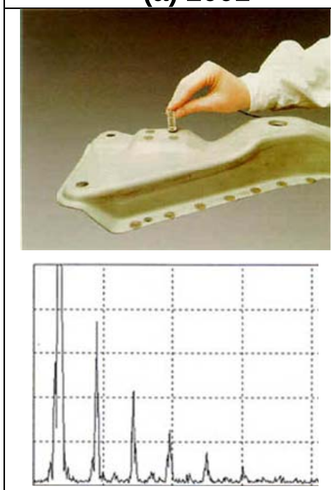
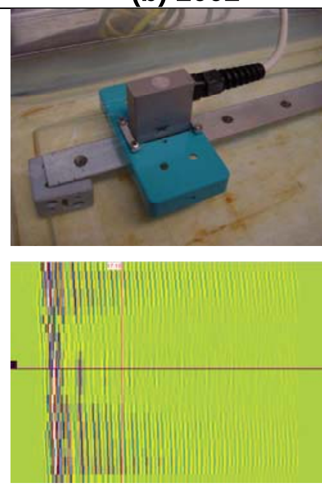
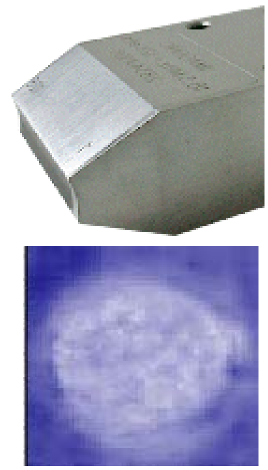
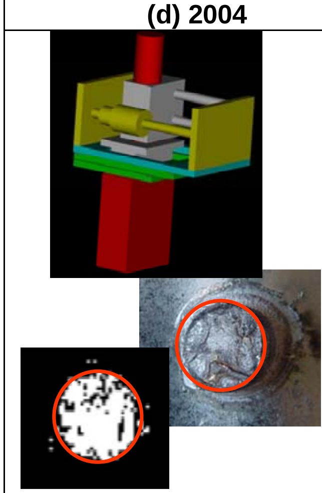
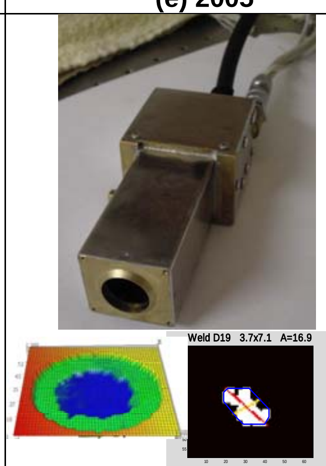
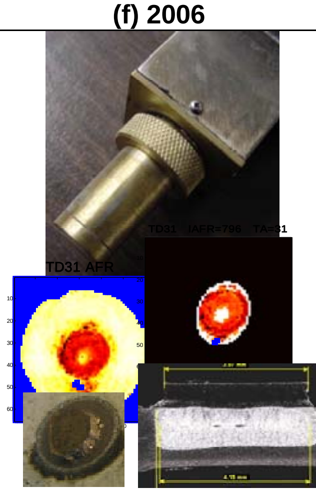
(a) 2001	(b) 2002	(c) 2003
		
Conventional ultrasonic inspection systems evaluated. Single-crystal probe at 20 MHz with digital analyzer and water column to obtain one signal to be interpreted to assess weld quality.	32-element phased-array probe working at 5 MHz used in a water tank to obtain an unprocessed B-scan. Measurements also made with a 10 MHz probe.	Focused (curved elements with a focal length of 37mm) 80-element linear probe working at 17 MHz used with symmetric delay laws and a mechanical scanner in a water tank to produce an unprocessed C-scan.
(d) 2004	**(e) 2005**	**(f) 2006**
		
Probe housing and miniature mechanical scanning system designed. More than 4,000 signals measured and analyzed in a few seconds. Signal processing implemented.	Integrated probe and scanner fabricated. Several cycles of testing and redesign for measurements on production parts. Software implemented to create indentation maps and dimension processed images.	Signal processing to extract diagnostic measures. Correlation studies and modeling to predict button areas from UT signals. Metallography for verification. Gage Repeatability and Reproducibility.

Figure 19-1. Evolution of Custom Hardware and Software Developed

20. Powder Metal Performance Modeling of Automotive Components (AMD410)

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- General Motors Corporation
- Metaldyne Sintered Components
- Materials Technologies Consulting, LLC
- Center for Advanced Vehicular Systems (CAVS)

Project Duration: October 2004 – March 2010

20.1 Executive Summary

Unlike other material processing technologies, the powder metallurgy industry lacks the simulation capability to readily evaluate design. Computer simulation models are needed to aid in the identification and risk of execution for the next generation of powder metallurgy conversions; i.e. gearing, control arms, etc. Past history has shown typical conversion saving to be in excess of $3M. For this reason an increasing number of automotive components are being converted to powder metallurgy technology. In order to properly engineer these components, it is necessary to understand the material and processing methods to obtain the mechanical behavior appropriate to the application. The accurate simulation of material behavior is vital for prediction of the performance of structural components. The approach is to develop and validate predictive models that describe the performance of non-forged powder metallurgy components to reduce design time, development costs, and aid in optimizing component weight and performance.

This project created powder metal compaction, sintering and performance computer models and validated them using an engine main bearing cap. The models successfully predicted component performance where traditional computer models failed. The models proposed alternative designs that reduced weight by weight of 3.8%, while increasing the monotonic strength by 5%, and the fatigue life by 9.5% utilizing the same iron-carbon powder. The project also identified opportunities to apply the models to aluminum and metal matrix composites using the same main bearing cap as a demonstration component.

The purpose of this project was to develop and evaluate math-based models for powder metallurgy component design and performance prediction. An existing United States Automotive Materials Partnership (USAMP) microstructure-property model for castings was extended to powder metallurgy for practical application in low strain rate (design and durability) and high strain rate (toughness driven impact strength) environments. The developed models allow the user to evaluate and optimize component design, as affected by material and manufacturing processes (compaction and sintering). Expected benefits from this project are as follows:

- Significantly shorten lead-time from concept to implementation: quick-to-market.
- Eliminate prototype components: reduce testing, material and manpower requirements
- Right the first time: reduce development time and investment from design to finished parts (die and design iterations).

- Optimize the products and processes in the virtual realm before committing resources to physical production.
- Use of modeling of die-compaction aimed to the choice of appropriate pressing diagram for complex shape parts and achieve a homogeneous green density distribution.
- Reduce the risk of lightweight material substitution.
- Improve component reliability.
- Mass reduction: design optimization.
- Large overall savings in total manufacturing cost.
- Enable use of technology to produce large powder metallurgy components.

20.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project was divided into four tasks:

Task 1—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.

- Determined material constants for FC-0205 and FC-0208 iron-carbon powders
- Determined material constants for Al-6061 aluminum powder

Task 2—Evaluate and develop numerical modeling techniques to predict mechanical properties throughout powder metallurgy component sections. The transition of current materials/design requirements to advanced structural powder metallurgy components has created a need to predict the properties of components in all sections of design. In addition, design processes should consider the least cost, lowest mass product designs and reduced development lead-time. The team extended an existing math-based framework with the abilities to predict powder metallurgy component structures and properties accurately throughout the compaction and sintering processes (section size, density variation, dimensional tolerances, potential for cracking), and with the input of alloys and process parameters (machine functions, tool and powder temperatures, friction and pressure). The team captured the history of a powder metallurgy part through its pressing, sintering, and lifecycle performance using the developed multi-scale methodology.

- Developed compaction, sintering and performance computer models.
- Evaluated the process history of target engine main bearing cap component.

Task 3—Develop component and vehicle level testing to validate durability, quality control and performance of powder metallurgy parts. The team determined quality control process factors (powder properties, press settings, tooling design, and furnace conditions) for powder metallurgy parts production in terms of their impact on process variations and quality improvement. The team used optimization and statistical techniques to help determine the main factors affecting the final component. The team performed validation experiments considering actual boundary conditions from real processes to fracture of the components.

- Validated compaction and sintering models by comparing predicted density and material properties to production engine main bearing caps.
- Validated performance model by comparing predicted component fatigue performance against small volume fatigue bench test results.

- Demonstrated lightweight material opportunities for the main bearing cap using aluminum 6061 powder.
- Proposed alternative designs for the main bearing cap that could yield weight savings and performance improvements.

Task 4—Perform technology/commercial transfer throughout the product value chain. To date, there exists limited accountability for major R&D/technical institutions to foster the infrastructure to support large-scale applications of powder metallurgy components. If the auto industry wishes to take advantage of powder metallurgy's potential weight and cost reduction opportunities, they must nurture powder metallurgy development through collaborative programs. The project team will request the professional support of societies to publish notices of meetings and project information, as released by the project team.

- Held a technology transfer session in October, 2008 with the Center for Powder Metallurgy Technology and Metal Powder Industries Federation.

20.2.1 Computer Modeling Work

Developed compaction, sintering and performance computer models as described in previous sections.

20.3 Deliverables/Products Developed

- Predictive models for powder metallurgy processes for further validation.

20.4 Technology Transfer Activities

20.4.1 Proprietary Reporting

- AMD Offsite talks and DOE Semi-Annual Reports.
- Held a technology transfer session in October, 2008 with the Center for Powder Metallurgy Technology and Metal Powder Industries Federation.

20.4.2 Non-Proprietary Publications and Proceedings

[1] Stone, T.W. et al., "Process Modeling: Use of Uncertainty, Sensitivity and Optimization Techniques for Improved Understanding of Compaction Model Outputs."

[2] DOE Annual Reports.

21. Thermal Drilling Application Development (AMD501)

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- Atlas Copco
- EJOT
- REMINC
- Acument Global Technologies
- Danly Tool
- ATF
- Visteon
- Bosch
- Gen Fast
- DOE PNNL & ORNL

Project Duration: October 2005 – March 2007

21.1 Executive Summary

The objective of this project was to demonstrate the feasibility of thermally drilling holes in a variety of steels and light metals that are of interest to the automotive industry. Diverse product forms of interest include sheet stock, thin-walled castings, rolled shapes, extruded tubing, and hydroformed shapes. Thermal drilling is a process similar in concept to friction stir welding in which the frictional heat of a spinning tool bit causes the material to soften and deform, thus opening up a hole and at the same time extruding material from the exit side. The latter forms a bush that effectively lengthens the hole, a joint strengthening advantage when threading the hole to insert a mechanical fastener. Displacing the material rather than generating cutting chips is a significant advantage in waste disposal. The thermal drilling bush could replace conventional weld nuts, enable drilling of certain parts on which the insertion of a nut from the inside is problematical, avoiding the need to cast-in bosses, and enable simpler part designs. A wide variety of parts can be improved by thermal drilling fastener holes. These include chassis sections, brackets, dashboard components, and frame rails. The weight-saving advantages of thermal drilling are further augmented by the fact that thermal drilling requires no coolant fluids and generates few if any cutting chips.

21.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Eleven alloys, some of which comprised several thicknesses and product forms, were selected for study and provided to ORNL by USAMP team members. Thermal drilling bits were provided by two companies (Flowdrill™ and Danley Tool, a supplier for Formdrill™). Some of the bits were purchased and some tools were in-kind contributions to the effort. A CNC vertical milling machine was used to thermally-drill the alloys using conditions that were found by ORNL staff to be suitable. As proof-of-concept, most holes were drilled for metric (M6) fasteners, but several holes were also drilled for M8 fasteners. Holes were subsequently tapped and the bush lengths were measured. After milling to remove the bosses or burrs at the in-feed side of the holes, plates were sent to Pacific Northwest National Laboratory (PNNL) for clamp load testing on a specialized test rig.

During the course of the project, it became clear that several different kinds of responses to thermal drilling can occur, and these largely had to do with the quality of the extruded bushes. In some cases, a nice, uniform conical bush was formed. There were usually some crenulations (thin, jagged edges) at the exit end of the bush, but these commonly broke off during the subsequent tapping operation. Sometimes, there were tears in the bush. Some were short, but others extended as far up the bush as the rear surface of the original workpiece. Sometimes, there were so-called “flower-petal” defects that peeled back from the hole and could not be used for tapping.

Based on a visual examination of the as-formed bushes, the thermal drilling characteristics were grouped into four categories:

> Category A: “Good” – Can be thermally drilled with relative ease so as to produce suitable, tapped holes.
>
> Category B: “Special Processing” – Thermally-drillable but requires certain auxiliary, special processing steps to ensure acceptable hole characteristics.
>
> Category C: “Marginal” – Potential to be thermally-drilled, but requires further process development to improve the results. Such additional work was beyond the scope of this effort.
>
> Category D: “Poor” – Current results did not indicate that this material could be thermally drilled with acceptable hole quality.

Table 21-1 lists the alloys and product forms evaluated for thermal drilling along with their general ratings that were based on the appearance of the as-drilled hole. A listing of suitable, but not necessarily optimal, drilling speeds, in-feed rates, and special procedures to produce acceptable holes in each A-, B-, or C-rated alloy can be seen in Table 21-1. The fact that a given alloy or product form is rated D does not definitely rule out thermal drilling for that material, but suggests that additional effort would be required to achieve suitable results.

An alloy’s response to thermal drilling depends on its properties, thickness, and microstructural condition. Therefore, the same thermal drilling conditions cannot be used for all materials. The spindle speeds for aluminum and magnesium alloys were considerably higher than those for steel. The pick-up (adhesive transfer) of aluminum and magnesium materials onto the thermal drilling bits causes a rise in friction and contributes to less precise control of hole dimensions than was observed in the steels where such pick-up was minimal. Special auxiliary processes, like the use of small pilot holes, application of drilling paste, and pre-heating the workpiece were applied in some cases. A special fixture was designed and built to study the effects of pre-heating on cast aluminum alloys, but pilot holes were more effective than pre-heating (up to 260°C) in producing usable extrusions in aluminum and magnesium. Auxiliary processes were not always successful in producing suitable holes for threading.

Clamp load tests of thermal drilling samples provided very good results in many cases. In some instances, as for steels thicker than 2.0mm, the fastener broke rather than stripping the threads, suggesting that the added thread lengths provided by the thermal drilling increased maximum clamp load.

In summary, thermal drilling was found to be a promising technology for weight saving in the manufacturing of automotive components from certain metals and alloys, notably high-strength steels like DP600 and DP780. It also shows promise for both aluminum and magnesium alloys, but for magnesium die-cast plates, the microstructure at the drilling locations made a difference between acceptable and unacceptable as-drilled hole quality.

Table 21-1. Alloys, Product Forms, and Thermal Drillability Ratings

Alloy	Designation	Form and Thickness	Category
Aluminum	A380	Die casting (4.1mm)	B
	A319-T5	Die casting (4.1mm)	B
Magnesium	AZ91	Die casting (1.5, 3.0, 6.0mm)	C
	AM60	Die casting (3.0mm)	B
	AE44	Die casting (3.0mm)	C
	AM50	Die casting (3.0mm)	B
Steel	DP600 HSS	Sheet	A
	DP780 HSS	Sheet Hydroformed shape	A
	HSLA50 HSS	Sheet	A
	TRIP900 HSS	Sheet	D

21.3 Deliverables/Products Developed

- An analytical model for thermal drilling (also known as friction drilling).

21.4 Technology Transfer Activities

21.4.1 Proprietary Reporting

- AMD Offsite talks and DOE Semi-Annual Reports.

21.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

22. High-Integrity Magnesium Automotive Components (AMD601)

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- CMI Novacast
- Altech LTD
- T-Mag PTY Ltd
- GS Engineering
- Worcester Polytechnic University
- Arizotah Global Enterprises LLC
- Purdue University
- CANMET
- Case Western Reserve University
- University of Iowa
- International Magnesium Association
- North American Die Casting Association
- American Foundry Society

Project Duration: April 2006 – March 2010

22.1 Executive Summary

This project addressed the near and mid-term metal casting development needs that were identified and previously published in the *Magnesium Vision 2020* document. Understanding and eliminating the technical barriers that currently inhibit magnesium casting production will move the automotive industry into a better position to realize emerging automotive magnesium component requirements, build magnesium industry infrastructure and develop tools that will be required to reduce the cost of magnesium components and enable sustainable production requirements. The object of this project was to: demonstrate that existing aluminum casting processes (Squeeze Cast and Low Pressure Permanent Mold {LPPM}) could be re-facilitated to cast magnesium alloys; investigate and develop the new emerging magnesium casting processes of Ablation and T-Mag; investigate and develop the use of an electro-magnetic pump to move molten magnesium; investigate and solve the critical technical barriers inhibiting magnesium application and component affordability, and deliver the same magnesium control arm from all processes for further evaluation and testing.

This project successfully demonstrated the technical feasibility of casting Mg AM60 and/or AZ91 alloys for all processes that were investigated, and all processes did successfully produce the same identical control arm with complete fill. However, not all processes produced a control arm with exactly the desired results (porosity, x-ray levels; exterior appearances, material properties etc), as those achievements depended on the time and personnel that was allocated to develop each process.

22.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The purpose of this project was to develop (existing and new) metal casting process technologies and tools required to manufacture cost-effective high-integrity cast magnesium automotive chassis components and increase production of magnesium components requiring geometries and properties not possible with existing high-pressure die-casting (HPDC) process limitations. High-integrity castings are defined as sound castings with low porosity (meeting ASTM E-155 Grade B or better), free of objectionable oxides and inclusions, with consistently high ductility and strength. This project developed existing aluminum low-pressure permanent mold and squeeze casting processes for the production of magnesium structural castings that could be used as suspension and chassis components. Processing costs as well as technical and manufacturing issues for each process were developed and validated; limited parts were produced, investigated for material properties, analyzed by non-destructive evaluation and tested both by static/vehicle methods.

HI-MAC research promises to broaden the range for potential cast magnesium 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 has investigated and evaluated new and emerging technologies and developed tools that address critical technology barriers currently inhibiting magnesium application and component affordability. Casting process and tool development were demonstrated by production of a magnesium control arm by low-pressure cast, squeeze cast and a new emerging casting process. Control arms were delivered for static and/or vehicle testing.

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

Task 1 – Squeeze casting process development—Squeeze casting is considered a “high-integrity” casting process because it imparts qualities to a metal that are difficult to achieve with conventional casting techniques such as HPDC. Squeeze casting can provide higher tensile properties and improved ductility due to reduced or absence of porosity in the matrix, and the ability to heat treat the cast component. In recent years, the squeeze casting process has been widely used with various aluminum alloys to manufacture near-net shape automotive components requiring high-strength, ductility or pressure tightness. Preliminary squeeze cast research has demonstrated technical feasibility potential for magnesium. Continuation will focus on applying this preliminary research for the production of an automotive component

Task 2 – Low-pressure casting technology—The American Foundry Society Magnesium Division has identified low-pressure permanent casting process and variant related technologies (VRC/PRC, PCPC etc.) as the shortest route to procurement of magnesium structural automotive components. The Magnesium Low Pressure Development (MLPD) project, funded as part of the USAMP SCMD project, demonstrated concept and technical feasibility and began magnesium low-pressure process development. MLPD successes included:

- Increased understanding of the effect of pressure application on magnesium fluidity and feeding.
- Improved understanding of microstructure and grain refining techniques.
- Validation of alternative protective cover gas technology.
- Development of a mold coating for magnesium permanent mold casting.

HI-MAC built on MLPD knowledge-base and demonstrate the production potential for automotive suspension components through process validation and limited production of LPPM cast control arms. HI-MAC research has also validated a magnesium permanent mold coating.

Task 3 – Thermal treatment—The American Foundry Society Magnesium Research Committee has completed preliminary research into alternative magnesium heat treatment cycles that can lead to significantly lower costs of magnesium cast components, including preliminary investigations into fluidized bed heat treatment of magnesium alloys. Magnesium alloys typically require long solution and aging cycles to achieve the desired mechanical properties, and this can add increased costs to heat treated magnesium castings. By heat treating in a shorter time frame, the heat treat costs for magnesium components can be one-third their current costs and less than the costs of conventionally heat treated aluminum castings. There is evidence in the literature on wrought magnesium alloys that a multi-step solution and aging treatment can add significantly to the mechanical properties of magnesium components, yet little work has been done to investigate the potential effect of a multiple step heat treatment process for magnesium castings.

Task 4 – Microstructure control—Casting microstructure is a key factor in component mechanical and fatigue properties. Development of microstructure through grain refining in aluminum alloys is well established. There are some reasonable techniques for the grain refining of aluminum containing magnesium alloys. However, the current method used to grain refine the high-temperature magnesium alloys includes using zirconium additions, which are costly and difficult to control in the production volumes required for potential automotive applications. Recent research has improved our understanding of magnesium metallurgical issues, defect formation and microstructure, but additional work was required to produce new methods and materials for grain refining and microstructure assessment.

Task 5 – Computer modeling and properties—Casting simulation suppliers and researchers have improved the state of simulation software, as new models have been developed and are being utilized by multiple foundries. Recent examples include models and new software modules for prediction of porosity in steel and aluminum alloys, hot tears and re-oxidation inclusion formation in steel castings, and thermo-physical properties for a variety of iron- and nickel-based alloys. While some preliminary work has been done on the solidification and fluid flow modeling on a few of the magnesium alloys, none of these advanced features are available for magnesium alloy casting.

Task 6 – Controlled molten metal transfer and filling—Low-pressure casting has been identified as the highest short-term potential for production of cast magnesium components for automotive power train and suspension components. Development of a molten magnesium pump is critical to low-pressure casting development, since an open furnace vessel can be used, enabling better access for grain refining and metal handling than the typical sealed low-pressure vessel. The materials and technology used in current molten metal pumps are not suitable for use in molten magnesium. While materials may exist that will provide the long-term resistance to molten magnesium corrosion, testing and development work is needed to develop the right combination of materials and technologies for maximum magnesium pump longevity. Current aluminum pump technology will need to be improved to control the fill profiles with the precision required for low-pressure magnesium casting.

Task 7 – Emerging casting technologies—
A new casting process (Ablation) using an aggregate mold will be evaluated to cast magnesium based alloys for automotive components. The casting process allows metal to fill the mold quiescently followed by rapid solidification rates equaling or exceeding die-cast cooling rates and enabling sound cast structures to be created. The mold is removed in under 120 seconds after completion of pour,

preventing contraction of the cast structure and mold from thermal stress interaction. Technical feasibility has been demonstrated for aluminum castings. Preliminary experiments in magnesium have demonstrated concept feasibility. This continued investigation will determine technical feasibility, define potential mechanical properties and explore the potential for casting magnesium components.

Task 8 – 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 magnesium components. It is for this reason, that if the auto industry wishes to take advantage of magnesium's potential weight-reduction opportunities, it will have to nurture it through programs. This program will only have a significant impact on North America's ability to use more magnesium if the Tier-1and Tier-2 suppliers and trade associations participate in this project.

Key Accomplishments:

In conclusion, the main HIMAC project accomplishment include:

- Four selected aluminum casting processes (Squeeze Cast; LPPM; Ablation; T-Mag) have been developed for AM60 and AZ91 magnesium alloys. Magnesium control arms were successfully cast from all processes that meet the project's SOW requirements and x-ray ASTM E-155 Standards of Level 2 or less.
- The electromagnetic pump (Task 6) was completed and installed in the LPPM machine and calibration tests are currently being performed before casting were produced.
- Modeling techniques were identified to minimize hot tear and porosity. The success of this model (Task 5) was proven when implemented in the Squeeze Cast process.
- Castings have been thermally treated with the advanced fluidized bed system (Task 3) significantly reducing cycle time from a typical eight hours to two hours.
- New research and development laboratory procedures were developed (and proved effective) for grain refinement (Task 4) using high-intensity ultrasonic vibration for improved dispersion of nanoparticles in molten alloy solidification behavior.
- The Magnesium Vision 2020 document (developed by the Structural Cast Magnesium Development project) was used as reference by the HIMAC project team as the new magnesium casting processes were developed.
- Seven different universities were actively involved in the HIMAC project, including student from undergraduate to doctoral levels.

22.2.1 Computer Modeling Work

See Task 5 information in the section above.

22.3 Deliverables/Products Developed

- Cast magnesium control arm for testing.
- Validated casting process technologies for production of cast magnesium automotive components.
- Computer modeling capabilities.
- Alternative thermal treatment procedures.
- Improved grain refining techniques and procedures.
- Cost information/process comparisons for four casting processes.

22.4 Technology Transfer Activities

22.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

22.4.2 Non-Proprietary Publications and Proceedings

[1] Pokorny, M.G. et al., "Prediction of Deformation and Hot Tear Formation Using a Viscoplastic Model with Damage in Shape Casting," 3rd International Symposium, Warrendale, PA, pp.265-272, 2009.

[2] Beckermann, C., "Prediction of Porosity and Hot Tears in Magnesium Casting," Materials Science and Technology 2007 Conference, Detroit, MI, September 2007.

[3] Xue, Y. et al., "Microstructure-Based Multistage Fatigue Modeling of Cast AE44 Magnesium Alloys," *International Journal of Fatigue*, Vol. 29, pp. 666-676, 2007.

[4] Kadiri, E. et al., "Fatigue Crack Growth Mechanisms in a Die Cast AM50 Alloy," *Acta Materialia*, Vol. 54, pp. 5061-5076, 2006.

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23. Development of High-Volume Warm Forming of Low-Cost Magnesium Sheet (AMD602)

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- Pacific Northwest National Laboratory

Project Duration: October 2006 – December 2009

23.1 Executive Summary

The major barrier to the application of magnesium sheet components in vehicle structures is a combination of two factors: the limited formability of magnesium sheet and the cost of producing the sheet itself. Warm forming processes similar to what was demonstrated in aluminum with the USAMP Warm Forming Project (AMD307) can be used to significantly improve the formability of magnesium sheet. This current project leveraged the accomplishments of the AMD307 Warm Forming project to develop equipment, lubricant, simulation and forming equipment for the cost-effective forming of magnesium sheet. A warm forming cell based on the lessons-learned of AMD307 was designed and built to demonstrate the efficient forming of magnesium sheet. The target application for this process was deep draw panels with specific interest in door inners.

The cost of magnesium sheet is driven by the high conversion costs of rolling an ingot into sheet form. This is a direct result of the HCP (hexagonal close packed) structure of magnesium that requires the sheet to be rolled in small increments often with annealing steps between rolling passes. Continuous casting is a technology with the potential to reduce this cost dramatically. By casting directly into sheet form, continuous casting offers a higher production rate, a smaller capital investment, and significantly less energy and labor as compared with the conventional direct-chill ingot-casting process. The opportunities for decreasing the cost of magnesium sheet via continuous casting have been described by Hunt et al. in their 2005 report to the DOE. Suppliers globally are working on developing continuous casting technology. In this project, all of the major global magnesium suppliers have been included to determine if their materials are suitable for the warm forming process. The new warm forming system was used as a standard test bed for the evaluation of these materials and will be for new magnesium sheet materials produced in the future.

The project included magnesium sheet from five major global magnesium suppliers. This includes two DC-casters [Magnesium Elektron (MENA) and ThyssenKrupp] and three continuous casters (CSIRO, Yinguang, and POSCO). Additional investigations into these materials were carried out at the University of

Virginia, CANMET-MTL in Ottawa, Ontario, and Pacific Northwest National Laboratory (PNNL). Reports from the PNNL work are not included in this document.

23.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objectives of this work were to develop both the technology and material supply base for cost-effective lightweight body panels fabricated from sheet magnesium. A warm forming system was designed and built to develop a suitable process for forming magnesium sheet as well as a test bed to evaluate potential low-cost magnesium sheet from various global producers. Specific deliverables of this project include:

- Design and build a warm forming die and demonstrate a deep draw capability on conventional direct chill material.
    - Demonstrate pan forming of at least 100mm.
- Evaluate materials and compare the formability of continuous cast and direct chill materials.
    - Evaluate high-temperature elongation of continuous cast material as compared to direct chill material.
- Demonstrate high-volume cycle times with continuous cast material on an integrated forming cell.
    - Part-to-part cycle time with continuous cast material of 5-10 jpm (jobs per minute).

<u>Technical Approach</u>:

- Continuous casting is a key technology for enabling the development of low-cost magnesium sheet. One objective of this work was to drive material development in the supply base by giving them a mechanism for evaluating materials. The project received material from major global magnesium suppliers including Magnesium Elektron, CSIRO, ThyssenKrupp, LY Copper, and POSCO. These materials were characterized via tensile testing at the University of Virginia, biaxial forming at CANMET, and through stamping trials at Troy Tooling Technologies.
- Novel die systems were designed and constructed that enabled the use of warm forming in a conventional single-action presses. The die was used to determine critical forming parameters for magnesium sheet including lubricant thickness, pre-heat temperature, die temperature, forming speed, etc. The forming windows for the different materials were determined to see the effect of processing via different methods, e.g. continuous casting vs. ingot (direct chill) casting.
- Full automation including loading of pre-heated sheet and part extraction was developed to achieve acceptable cycle times (5-10 jpm) demonstrating the high-volume feasibility of warm forming.

<u>Accomplishments</u>:

- Developed die architecture and process to provide thermal stability/uniformity to minimize dimensional distortion during steady-state production conditions.
- Demonstrated the formability of the continuous cast alloys with both tensile testing, lab-scale formability experiments and full warm forming trials. Developed forming limit curves at CANMET for all test alloys at two different temperatures.
- Completed the material characterization work through microscopy, elevated temperature tensile testing and formability experiments on alloys from five suppliers.
- Completed full-scale forming trials and determined forming windows for all

magnesium sheets with respect to temperature, binder pressure, lubricant and blank size.

- Developed finite element prediction methods of forming and failure during warm forming.
- Developed fully-automated warm forming cell capable of demonstrating the process under run-at-rate conditions at five jobs per minute for both aluminum and magnesium sheet.

Conclusions:

- Successful completion of two projects on warm forming has shown that this technology can be used as a cost-effective method of manufacturing complex 3D panels from both aluminum and magnesium sheet.
  - AMD307—the process was demonstrated in a prototype mode on a one-piece door inner that was not feasible in either aluminum or magnesium at room temperature.
  - AMD602—a purpose built die was integrated into a fully-automated forming cell to demonstrate the process under run-at-rate conditions.

23.3 Deliverables/Products Developed

- Die architecture and process.
- Finite element prediction methods of forming and failure during warm forming.
- Warm forming die.

23.4 Technology Transfer Activities

23.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

23.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

24. Magnesium Front-End Design and Development (MFEDD): Design and Feasibility Study (AMD603)

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- Camanoe Associates
- Magna
- EDAG
- ETA
- Porsche Engineering
- MSX
- Multimatic

Project Duration: October 2006 – March 2010

24.1 Executive Summary

This project is to carry out design and technical cost modeling studies of a complete magnesium-intensive front-end structure for a rear-wheel-drive (RWD) unibody and a magnesium upper structure for a body-on-frame architecture. It is expected that the resulting magnesium front-end designs will offer significant mass saving (60% to steel) and performance improvement as well as reduced emissions.

This project will leverage a proposed U.S.-Canada-China collaboration on magnesium front-end research and development (MFERD) on the development of key enabling technologies, fundamental research and component manufacturing. The USAMP magnesium front-end design and development (MFEDD) project will be coordinated with the USAMP Multi-Material Vehicle (MMV) R&D Initiative.

Due to the use of larger powertrains, most current North American vehicles are front-heavy with a front-to-rear mass ratio above 55/45. Front-end mass reduction and a near 50/50
mass ratio are very important to vehicle fuel economy, driving and handling performance. In 2005, BMW introduced an aluminum front-end structure in its 5/6 series cars to reduce mass and achieve a near 50/50 mass distribution, at considerable cost penalty compared to steel. Based on the better castability of magnesium compared to aluminum (especially in making large thin-wall castings for part consolidation) and the overall reduction in cost of the primary metal, it is believed that a magnesium-based front-end structure can be designed and manufactured at near cost parity compared to steel.

24.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objective of this project is to leap-frog the aluminum front-end technology to design and develop a lighter-weight magnesium front-end structure for the ongoing USAMP MMV program in which advanced high-strength steels (AHSS) and polymer composite materials will also be used.

The primary goal of this project is to develop lightweight magnesium front-end designs for a rear-wheel-drive unibody and a body-on-frame architectures meeting the following objectives:

- Mass reduction: 60% (40 kg) lighter than steel; and 35% (16 kg) lighter than aluminum for a mid-size passenger car.
- Shift the front-to-rear mass ratio by ±1 towards 50/50 for the rear-wheel-drive unibody architecture.

- Maximum of $8/kg of mass saved (based on 100,000/year production volume) via the part consolidation using large magnesium castings such as dash panel and shotguns and the overall decrease in cost of magnesium in world markets.
- 5-star frontal and offset impact crash ratings for the “donor” vehicle with the magnesium front-end (simulation).
- Match or improve the key performance criteria such as stiffness, durability and noise, vibration and harshness of the MMV “donor” vehicle (simulation).

Major accomplishments included identification of crashworthiness limitations of the magnesium alloy front rails in the unibody structure and replacement with aluminum extrusions, and sensitivity of the cost structure to certain joining attributes and corrosion protection. Although the original weight reduction target of 60% for the unibody structure was not achieved, the 45% reduction outcome approaches the overall program target of 50%. Also, the 44.3 kg total mass reduction for the magnesium-intensive unibody front-end design exceeded the original 40 kg goal.

24.3 Deliverables/Products Developed

- Magnesium front-end design data, CAE models and cost modeling results for two architectures (complete unibody front-end and body-on-frame upper structure), with one of them being the common architecture with the MMV program.

24.4 Technology Transfer Activities

24.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

24.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

25. Magnesium Front-End Research and Development (MFERD) Enabling Technology Development (AMD604)

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Project Duration: October 2006 – March 2010

25.1 Executive Summary

Despite recently increased magnesium applications in North America and Europe, automotive applications of magnesium remain at single components level and dominated by casting applications. To evaluate the viability of magnesium as a major automotive structural material for vehicle mass reduction and performance improvement and to develop enabling technologies for magnesium castings and wrought products, a large-scale magnesium development project is needed to bring the magnesium applications from single component level to a subsystem level.

Front-end mass reduction and a near 50/50 front-to-rear mass ratio are very important to vehicle fuel economy, driving and handling performance. In 2005, BMW introduced an aluminum front-end structure in its 5/6 Series cars to reduce mass and achieve a near 50/50 mass distribution, at considerable cost penalty compared to steel. Based on the better castability of magnesium compared to aluminum (especially in making large thin-wall castings for part consolidation) and the overall reduction in cost of the primary metal, it is expected that a magnesium-based front-end structure can be designed and manufactured at significantly lower cost compared to aluminum and at near cost parity compared to steel.

The objective of this project is to develop key enabling magnesium technology in high-integrity body casting, extrusion, sheet forming, corrosion protection, joining and assembly for a lighter-weight magnesium front-end structure. Research tasks will also be pursued to address magnesium technology in crashworthiness, noise, vibration and harshness, fatigue and durability.

25.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The primary goal of this project is to develop key enabling technologies (body casting, extrusion, sheet and joining) and knowledge-base (crashworthiness, noise, vibration and harshness, durability and corrosion) for primary (load path) body applications of magnesium alloys. The following are some specific objectives:

- Define materials and develop manufacturing processes for magnesium body castings, extrusions, sheet and joining technologies.
- Develop knowledge-base and define magnesium body technical requirements in crashworthiness, noise, vibration and harshness, durability, corrosion and surface finishing.
- Establish original equipment manufacturer/supplier/academia collaboration in magnesium body applications.

The project is divided into the following two phases:

Phase I – Enabling Technology Development

Task 1– Crashworthiness research—This task will determine the effect of high strain rates (as observed during crash tests) and anisotropic characteristics on the mechanical properties and energy absorption of magnesium wrought alloys (AM30 and AZ31) and cast alloy (AM50).

Work should also include the effect of processing conditions (forming and casting), and component design on the crashworthiness of automotive components such as longitudinal rails (wrought) and shotgun (high-integrity body casting and thixmolding).

The crashworthiness design studies will consist of both computer-aided engineering analyses (using LS-DYNA® or equivalent crash analysis code) and selected testing of prototype sections in crush (low loading rate) and crash (high loading rate) component tests. This task should also compare the crashworthiness of magnesium alloys with conventional aluminum alloys (5754 and 6063) as well as HSLA350 and DP600 on equivalent prototype sections/components.

Task 2 – Noise, vibration and harshness study—The noise, vibration and harshness study will focus on the sound transmission characteristics of cast magnesium alloys used in dash panels. The task will also include analysis of sound of different frequencies (such as powertrain and airborne and white noise at audible frequencies, 20-20k Hz) and the effect of dash panel features on the sound transmission.

The task will include feature investigations that include a single layer dash panel and a double-plate panel. Stiffness enhancements and mass removal at a specified performance target (e.g. objective function based upon frequency combinations) will be explored.

This task will also compare the tested noise, vibration and harshness properties of magnesium alloys with other materials such as aluminum and steel as well as a laminated dash panel from a typical production vehicle (0.75mm mild steel, foam layer, 0.75 lb/ft**2 EVA layer).

Task 3 – Fatigue/durability—This task includes research on the fatigue behavior of magnesium body castings, extrusions and sheet products. The effect of alloy design, processing and microstructure on the fatigue properties of magnesium alloys will be studied.

Multi-axial fatigue testing of magnesium cast and wrought alloys will be carried out in this task. The durability of magnesium and dissimilar metal joints will also be included in this task.

Task 4 – Corrosion and surface finishing—This task will establish the surface finishing processes required for automotive body applications. Surface conditions such as as-fabricated (die-casting, semi-solid casting, extrusion and sheet formed), conversion coatings, anodizing, electrophoretic and powder coatings, will be evaluated for general and galvanic corrosion performance and assembly protection.

This task is also to select/develop accelerated corrosion test procedures that correlate with real world performance of magnesium body components in general and galvanic corrosion.

Task 5 – Low-cost extrusion development and forming techniques—The key in this task to develop/select magnesium extrusion alloys (AM30 and AZ31) with high extrusion speeds and improved mechanical properties. The extrusion process needs to be optimized for high speed (low-cost) and better microstructure. New extrusion alloys will also exploited for improved mechanical properties and extrudability.

Extruded magnesium tubes will need to be bent to form structural parts in the front-end. Key components include longitudinal rails and possibly a cowl bar (if can't be integrated into the dash panel casting).

Rotary draw bending and stretch bending processes will be investigated for magnesium tube bending. Moderate temperature bending might be needed. Gas forming of magnesium tubes will be exploited if needed.

Task 6 – Low-cost sheet development and forming processes—Twin-roll or twin-belt continuous casting process will be explored for low-cost production of magnesium sheet. Process will be optimized for best quality and productivity.

The task is also to develop the technology and material supply base for cost-effective lightweight body panels fabricated from sheet magnesium. A warm forming system will be developed and built to develop a suitable process for forming magnesium sheet as well as a test bed to evaluate potential low-cost magnesium sheet from various producers worldwide.

Task 7 – High-integrity body casting development—Current aluminum body castings (about 3mm wall) use special alloys (such as AURAL-2), developed by Alcan and Alcoa and licensed vacuum die-casting processes (such as the Alcan High-Q process), and therefore, are very expensive (typically two to three times of the conventional die-castings). The focus of this task is to develop high-integrity vacuum die-casting processes for magnesium alloys to produce cost-effective magnesium castings that are heat-treatable and weldable. Porosity reduction and ductility improvement and thin-wall capability (about 2-2.5mm) are some of the technical challenges.

Learnings from the ongoing USAMP projects (semi-solid casting in "Ultra Large Castings for Lightweight Vehicle Structures" (AMD406) and the ablation process in "High-Integrity Magnesium Automotive Components" (AMD601) will be used in this task for the U.S. activities.

Task 8 – Welding and joining—This task will investigate various welding and joining techniques for magnesium to magnesium, magnesium to steel and magnesium to aluminum joining.

Project AMD604 was formally concluded in March 2010 and successor project AMD904 was launched on April 1, 2010. Agreement among international partners in China and Canada of an agenda and budget for Phase II and development of supporting objectives at the national and international task team levels was achieved in March 2010. Initiation of Task 2.0 on design and acquisition of six candidate designs for the "demonstration" structure meeting selected criteria was launched.

Some of the accomplishments in AMD604 include: (a) development of super-vacuum die-casting technology – produced the first-in-the-world weldable magnesium die castings; (b) fabrication of low-cost continuous cast magnesium sheet with comparable mechanical properties and formability; (c) optimization of extrusion process parameters and process simulation tools; (d) demonstration of several magnesium and dissimilar metal joining and corrosion protection options – key to automotive applications; and (e) creation of significant knowledge-base and computational tools in magnesium crashworthiness, NVH, fatigue and ICME.

25.3 Deliverables/Products Developed

- Material and component test data (high-strain rate, fatigue, corrosion and NVH).
- Recommendations for coating and joining techniques.

- Process parameters for magnesium casting, extrusion and sheet forming.
- High-integrity casting process for magnesium body castings.

25.4 Technology Transfer Activities

25.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.
- Annual Tri-Country Project Review Meetings (2007 in USA, 2009 in China and 2009 in Canada).

25.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

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26. In-Line Resistance Spot Welding Control and Evaluation System Assessment for Lightweight Materials (AMD605)

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- Chrysler LLC
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- Tech Knowledge

Project Duration: October 2006 – March 2008

26.1 Executive Summary

Aluminum and advanced high-strength steel (AHSS) sheet materials represent substantial opportunities to save weight and improve fuel efficiency. Robust spot weld control and quality assessments are significant hurdles in the widespread implementation of lightweight materials such as aluminum and AHSS.

No economically reliable method exists today to inspect resistance spot welds at production rates. The current accepted practices make use of labor intensive, manual teardown inspection processes, performed every shift to determine weld quality off-line.

The objectives of this project were to assess the current state-of-the-art for in-line resistance spot welding (RSW) control and evaluation systems and to determine their potential for application to direct weld control for lightweight sheet materials.

First, various suppliers/developers of in-line RSW control and evaluation systems were invited to participate in the current study and subject their systems to the proposed assessment procedures/protocols. A team of welding experts from the automotive industry was assembled to provide assessment criteria/targets for performance, cost, and retrofit/integration potential. The team developed matrices of technical issues and business issues to be investigated and measured. Based on these matrices, detailed test and analysis protocols and questionnaires were developed to assess currently available RSW evaluation and control systems. Plans for fabrication of samples were made for the control systems that required them. Potential material sources for these samples were also identified.

After the business issues questionnaires and test protocols for both the in-line adaptive and post-weld audit systems were developed, they were sent to 15 system suppliers with an invitation to participate. Only four suppliers submitted responses to the questionnaires. Only two suppliers volunteered to participate in the testing of their systems. The remaining suppliers declined to participate.

Because of the lack of participation from various system suppliers in this stage of the project, the project team concluded that it was no longer possible to meet the project objectives and timeline for deliverables outlined in the Statement of Work, and decided to stop all development work.

The only technical needs identified in the project for further development consideration were in infrared thermography technology.

The final report details the creation of the technical and business issues matrices, system assessment protocols and business issues questionnaires developed in this project for RSW evaluation and control systems.

26.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

There were five technical tasks outlined in the statement of work:

Task 1 – Create testing procedure (issues matrices, questionnaires and test protocols)—Develop the step-by-step process to conduct assessments of various control and evaluation systems.

- A team of welding experts from the automotive industry was assembled to provide assessment criteria/targets for performance, cost, and retrofit/integration potential. The team developed matrices of technical issues and business issues to be investigated and measured.
- A Technology Issues Matrix was developed for in-line adaptive systems.
- A Business Issues Matrix was developed for RSW in-line adaptive systems to assist in understanding business related concerns to measure/evaluate impact to incumbent operations that may have affected implementation and adoption of the technologies.
- Based on the questions identified in the technical issues and business issues matrices, the team developed a weld sample fabrication protocol for in-line adaptive systems.
- Certain elements of interest to the project could not be collected from the physical test protocols. Some information, such as business issues, required a questionnaire or survey approach. Due to the sensitivity of the data requested, individual questionnaires were held in confidence and not shared with competitors. A secure internet survey site was contracted to collect responses.
- A Technology Issues Matrix for post-weld audit systems was developed.
- A Business Issues Matrix was developed for RSW post-weld audit systems to assist in understanding business related concerns to measure/evaluate impact to incumbent operations that may have affected implementation and adoption of the technologies.
- Based on the questions identified in the technical issues and business issues matrices, the team developed a weld sample fabrication protocol for post-weld audit systems.

Task 2 – Acquire and prepare materials and coupons for evaluation—Obtain all combinations of materials in size, shape, and thickness in order to exercise systems and support testing protocol defined in Task 1.

- Initial material availability search has been conducted inside other project teams within USCAR, Auto Steel Partnership (A/SP) and among original equipment manufacturers and suppliers. Corresponding material needs have been calculated and the weld population definitions have also been drafted.
- Sources for all the materials needed for the project have been identified. These sources include: Chrysler, General Motors, A/SP inventory and steel suppliers.

Task 3 – Exercise in-line systems to evaluate RSWs—Examine various in-line RSW control and evaluation systems and their performance using the testing process created in Task 1.

- During the course of the project 15 technology providers expressed interest in participating. Invitations to complete a questionnaire and participate in the test protocols were sent to all 15.
- Four technology providers elected to participate and submitted questionnaires.

All of the submitted questionnaires were for Post-Weld Audit Systems. One In-Line Adaptive Weld Control System provider agreed to participate, but did not submit a completed questionnaire.

- Due to the minimal number of responses, analysis of the submitted questionnaires was of limited value. In addition, most responses were based on assumptions, as none of the four respondents had systems in commercial resistance spot welding applications.

  The questionnaires did, however, identify the following technology development needs:

  - "Further testing and signal processing development is required to improve the sensitivity for stick weld detection" for laser ultrasonics.
  - "Weld indentation, porosity, and cracking need further investigation" for infrared thermography.

The project was terminated before this task was initiated.

<u>Conclusions</u>:

- Although the initial responses at the project kick-off meeting were overwhelmingly enthusiastic from many suppliers, the feedback to the business issues questionnaire and testing was sparse. Only four suppliers submitted responses to the questionnaires. Only two suppliers volunteered to participate in the testing of their systems. The remaining suppliers declined to participate.
- Both infrared thermography technology suppliers submitted questionnaires and identified potential technology needs. These needs were identified as measurement accuracy of cracks, porosity and indentation.
- Because of the lack of participation from various system suppliers in this stage of the project, the project team concluded that it was no longer possible to meet the project objectives and timeline for deliverables outlined in the Statement of Work, and decided to stop all development work.
- The only technical needs identified in the project for further development consideration were in infrared thermography technology.
- The team then proceeded with project closure tasks and notified AMD and USAMP of the team's decision.
- Technology questions and concerns still remain regarding the feasibility of control technologies to accurately identify key weld characteristics and defects that occur in the production process during nugget formation or immediately thereafter. Furthermore, no viable technologies exist for the inspection and control of RSW for advanced, lightweight, thinner gauge, high-strength steels and aluminum materials. As a result, as the industry moves toward body structures with more AHSS and aluminum, the post-mortem teardown inspection processes for weld integrity will be less reliable and more difficult and costly, potentially discouraging the implementation of these materials.
- This project team did develop sound tools to assess in-line RSW control and evaluation systems. Furthermore, it clearly communicated the expectations of the automotive manufacturing industry to the in-line RSW control and evaluation systems suppliers.

26.3 Deliverables/Products Developed

- A process used to assess current and proposed in-line RSW control and evaluation systems for lightweight materials.

- A Technology Issues Matrix was developed for in-line adaptive systems.
- A Business Issues Matrix was developed for RSW in-line adaptive systems.
- A Technology Issues Matrix for post-weld audit systems was developed.
- A Business Issues Matrix was developed for RSW post-weld audit systems.

26.4 Technology Transfer Activities

26.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.
- RSW Audit System Evaluation Matrix and Testing Procedure, AMD605 document, February 2007.
- RSW In-line Adaptive System Evaluation Matrix and Testing Procedure, AMD 605 document, April 2007.

26.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

27. Integrated Computational Materials Engineering for Magnesium (AMD703)

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- CANMET
- Mississippi State University

Project Duration: March 2007 – Present

27.1 Executive Summary

The goal of this project is to develop this key enabling technology for advanced lightweight magnesium processes and alloys for body structure and other body applications. The project will develop key databases and capture them in models to enable alloy and manufacturing process optimization for high-integrity magnesium castings, extrusions and sheet product. The scientific understanding in processing-structure-property relationships will be captured in a publicly available magnesium Integrated Computational Materials Engineering (ICME) cyberinfrastructure. This cyberinfrastructure will provide a platform for the integration of models from different domains to enable development of comprehensive and robust processing-structure-property relationships which can also be integrated with manufacturing simulation and design computer-aided engineering. The cyberinfrastructure will also provide a platform for the optimization of alloys, manufacturing processes and components. The program will be conducted as a research collaboration between researchers and organizations in Canada, China and the United States and will serve as an international pilot project for the new ICME movement within the materials profession.

A central requirement to be realized will be the development of a global infrastructure or protocol for information exchange and interfacing of models. This will include interfaces for different manufacturing processes simulation software with materials models and, in turn, with design analysis tools. Protocols must be developed to integrate hierarchical modeling approaches and to link microstructural evolution models with property models. To effectively harness the global knowledge-base, these infrastructures must enable geographically distributed modeling activities and allow networks to develop organically while protecting proprietary and security interests. This ICME for magnesium project will establish such an infrastructure for magnesium.

If the project goals are successfully achieved, the project will have the following benefits:

1. Demonstrate automotive industry leadership in a key new technology area (ICME).
2. Optimization of key enabling technologies for magnesium applications in primary body structures:
    - Low-cost, high-vacuum die-casting technology – weldable body castings.
    - Low-cost, wrought magnesium alloys – extrusion and sheet components.
3. Improved fuel economy and reduced emission through reduced vehicle weight.
4. Optimize cost, quality and performance of magnesium components.

5. Improve ability to conduct up-front engineering analysis, reduce prototyping requirements and reduce time-to-market.
6. Advanced magnesium infrastructure (R&D capability and supply base).

27.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The primary goal of this project is to develop an ICME infrastructure for magnesium alloy development and magnesium manufacturing process optimization. This is a key enabling technology for future magnesium body applications. The following are some specific objectives:

- Establish an international ICME infrastructure (contributor network, knowledge-base and cyberinfrastucture) for magnesium for body applications:
  - Product and manufacturing process optimization (processes include extrusion, sheet forming and high-pressure die-casting).
  - Microstructural engineering.
  - Future alloy development.
- Develop a web-based cyberinfrastructure to serve as a hub for exchanging high-quality data and models between global collaborators in academia and industry.
- Use ICME infrastructure for MFERD Phase II product and process optimization
- Attract materials researchers into magnesium field and leverage their efforts by providing a collaborative space for coupling high-quality data and models.
- Advance scientific understanding in various aspects of magnesium cast and wrought alloys for body applications, including development of processing-structure-property relationships, corrosion science, crash energy management, fatigue performance as well as design optimization.
- High-quality professionals and students educated in materials science and engineering the U.S., Canada and China.

27.3 Deliverables/Products Developed

- Establishment of an ICME capability for magnesium alloys and manufacturing processes of interest to the automotive industry.
- A user-friendly, publicly available, expandable web-based infrastructure for development of ICME models for wrought and cast magnesium alloys.
- A comprehensive set of processing-structure-property relationships for wrought and cast magnesium alloys (AM and AZ Series).
- The ability to use the ICME infrastructure and knowledge-base to optimize alloys, manufacturing processes and components for the automotive industry.

27.4 Technology Transfer Activities

27.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

27.4.2 Non-Proprietary Publications and Proceedings

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28. Development of Steel Fastener Nano-Ceramic Coatings for Corrosion Protection of Magnesium Parts (AMD704)

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Project Duration: August 2007 – Present

28.1 Executive Summary

The goal of this project is to develop cost-effective technologies to solve the notoriously difficult galvanic corrosion problems for fasteners of magnesium parts. The development will reduce the main inhibitors to using magnesium alloy in vehicles and expanding the applications of magnesium in the automotive industry. This project will directly impact the Magnesium Front-End project, MMV and all current/future original equipment manufacturers magnesium application programs by enabling low-cost/high-volume enabling steel fastener joint designs.

Because of its position in the galvanic series, magnesium is anodic to almost all other metals and the galvanic corrosion of magnesium parts is difficult to be cost-effectively mitigated by existing methods. For example, the current computer-aided machined bolts for mounting the production cradle, developed by the USAMP SCMD project, to the 2006 Z06 Corvette are causing relatively high extra costs. After trying different solutions with no cost-effective outcomes, one has realized that comprehensive deep R&D, involving fundamental understanding, various materials choices, and innovative concepts, is necessary to find the best of the best solutions for corrosion protection of fasteners of magnesium components.

28.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The key challenge when lightweighting with magnesium components are cost-efficient mitigation solutions for galvanic corrosion at magnesium/steel (fastener) interfaces. Specifically, galvanic corrosion of fasteners of magnesium parts is the most pressing issue that impacts long-term vehicle durability. The objective of this project is to develop nano-ceramic coatings that provide an electrical insulation barrier to stop or substantially mitigate galvanic electric current between the cathode (e.g. the steel, aluminum) and magnesium parts and provide durable service performance.

Approach:

- Thin-film coatings of ceramics and polymers will be used to electrically isolate steel bolts, nuts, washers from magnesium parts to stop the galvanic electric current to protect these parts from galvanic corrosion.
- An engineering-science-and-testing-based approach will be used to choose the ceramics/polymer materials and film thickness for the thin-coating layers. Literature review and analyses involving atomistic, micromechanics and electrochemical potential analysis will be conducted for galvanic corrosion mechanism, film stress and fracture theory, etc.
- Based on experience over last 15 years of ceramics film coating at Alfred University,

priority material candidates include silicon nitrides and aluminum oxides.

Phase 1 Accomplishments and Results

- Flat steel test specimens have been successfully coated with Al203 and Si3N4.
- Nano-ceramic coatings are shown to increase impedance modulus more than two orders of magnitude.
- Coatings indicate they are pre- and post-strain tolerant.
- Nano particle size is very important for strength and ductility.
- Learned how to characterize electrochemical results relative to fastener coating barrier corrosion performance.
- Recent corrosion test indicate that continuous uniform Si3N4 coatings provide a significant barrier.
- Initial cost analysis indicate piece price might be as low as ($0.005).

Project will continue to determine optimum coating particle size, thickness(es), number and order if multiple coatings are recommended.

28.3 Deliverables/Products Developed

- Coating formulations and characterization data.

28.4 Technology Transfer Activities

28.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

28.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Reports.

29. Nano-Engineered Cast Components Elevated Temperature Mechanical Property Testing and Cost Model Development (AMD705)

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Project Duration: January 2009 – January 2010

29.1 Executive Summary

Aluminum alloys have great potential for reducing the mass of vehicles, thereby significantly improving the energy efficiency of transportation systems. However, their mechanical properties, especially their property degradation at elevated temperatures, present a potential roadblock to their wider use in the demanding environments of advanced powertrain applications. It has been reported that the properties of aluminum alloys may be enhanced considerably if nanoparticles are used as reinforcement. It has also been reported that nanostructured aluminum materials have higher strength without accompanying lower ductility. It is proposed that a fine, uniform dispersion of nanoparticles can provide dispersion strengthening (as non-deforming particles, such as inorganic nanoparticles). They may also provide inter-particle spacing effects such as increasing the yield strength and creep resistance by mechanisms such as dislocation bowing around the particles and the pinning of dislocations at the particles by rapid diffusional stress relaxation at elevated temperatures thereby retaining the good matrix ductility. These benefits require only a small percentage of nanoparticles (less than 2%) in the casting. Nevertheless, the main limitation to wider use of nanoparticle reinforcement is the cost of the nanoparticles and of their processing (dispersion) into metal melts. It is anticipated that with increasing mass production, the cost of nanoparticles is expected to become significantly lower, which should make the production of nanostructured aluminum and magnesium cost effective.

The current processing methods for bulk nanostructured aluminum materials are limited in size and geometric complexity, preventing designers from achieving the design flexibility desired for complex automotive and aerospace structures. The potential of nanostructured aluminum materials cannot be fully developed for industrial applications unless complex structural components of the nanostructured aluminum materials can be fabricated cost-effectively, such as by casting. Nor can reliable nanostructured aluminum parts be cast unless nanoparticles can be dispersed and distributed uniformly in molten aluminum. Unfortunately, it is extremely challenging for conventional mechanical stirring methods to distribute and disperse nanoparticles uniformly in metal melts due to the large surface-to-volume ratio of the particles, and their poor wettability in most metal melts, which easily induces agglomeration and clustering. Thus, there is a strong need for a cost effective and reliable process that enables efficient and stable dispersion of nanoparticles in aluminum melts for casting of high-performance nanostructured aluminum materials.

Preliminary experiments demonstrated that ultrasonic cavitation is effective in dispersing and stabilizing ceramic nanoparticles in aluminum alloy melts for casting in small crucibles. Substantial basic research and development must be performed to establish an engineering science and technology base for a solid understanding of strengthening, deformation, creep, and fatigue mechanisms in the nanometer range. However, the project was terminated at Professor Li's request. Professor Li felt that he needed to accomplish more internal work before he could complete a set of specifications for sourcing silicon carbide nano-powder. The project team agreed and supported his decision.

29.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The Phase I project was aimed at measuring the elevated temperature tensile properties and fatigue properties of the A356 alloy nanocomposite and developing a cost model structure for fabricating this material.

<u>Conclusions</u>:

- The reported benefits of nanoparticle reinforcement of aluminum were not realized in this work. Experimental problems and inconsistencies in materials and handling are to some extent responsible for the results.
- Testing trials with two different powder sources revealed significant variations in chemistry, color (indicative of oxidation and impurities), and crystallinity (cubic vs. hexagonal). It is possible that these differences affected the tensile properties, but the results of the present work did not establish that.
- A characterization procedure was developed to analyze the incoming nano-powder material. This should provide the basis for generating a specification for silicon carbide powers.
- A processing procedure for the manufacture of the nano-aluminum material was developed. While following this procedure should improve the consistency of experimental results it remains to be shown.

Task 1 – Casting and mechanical test of A356 nanocomposites

- Developed an efficient nanoparticle feeding method.
- Conducted mold design and casting experiments.
- Created a processing procedure to ensure more consistent casting.
- Casting of A356 and its nanocomposite tensile specimens.
- Analysis of A356 tensile testing results.

Task 2 – Microstructural Characterization

- Scanning Electron Microscope Analysis of nanoparticle dispersion.
- Nanoparticle characterization and understanding.

29.3 Deliverables/Products Developed

- An incomplete processing procedure intended to achieve more efficient and higher integrity casting of aluminum.

29.4 Technology Transfer Activities

29.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

29.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Report.

30. Magnesium Front-End Research and Development (MFERD) Technology Development and Demonstration – Phase II (AMD904)

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- IHC (Anomag)
- MacDermid
- Magni
- Atotech
- Kamax
- Ohio State University
- Eastern Michigan University
- University of Michigan – Dearborn
- North Dakota State University
- Luke Engineering and Manufacturing
- TAG
- Applied Magnesium International
- Lehigh University
- SFTC
- Magnesium Elektron
- Missouri University of Science & Technology
- EKK
- U.S. Magnesium
- NADCA
- Gibbs Die Casting
- Meridian
- ATF
- REMINC
- Visteon
- MNP Corporation
- Dow Automotive
- Hitachi
- Robert C. McCune and Associates, LLC

Project Duration: January 2010 – Present

30.1 Executive Summary

Increasing worldwide energy demand due, in part, to emerging economies, coupled with probable peaking of conventional petroleum production in the coming decades, are increasing the need to reduce dependence on petroleum-based fuels for transportation. Vehicle lightweighting is a significant strategy to improve fuel economy of vehicles with conventional gasoline internal combustion engines or alternative energy powertrains. Magnesium, the lightest structural metal, has emerged as a promising material for lightweighting and become a focus of research and development in North America, China and Europe. Over the last few years, China has become the world's largest magnesium producer, supplying more than 80% of the world market in 2008. Magnesium components are gaining acceptance by major automotive companies including General Motors (GM), Ford, Chrysler, BMW, Volkswagen and Toyota.

Despite increasing magnesium automotive applications in North America, Europe and China, automotive magnesium applications remain principally at the single component level and dominated by die-casting applications. To evaluate the viability of magnesium as a major automotive structural material for vehicle mass reduction and performance improvement, a large-scale magnesium development project was envisioned by the progenitors of this project. It

was also deemed necessary to develop enabling technologies such as joining of magnesium castings and wrought products, in order to advance automotive magnesium applications from the single component level to the subsystem level.

The goal of this project is to develop, build and test a magnesium demonstration structure relevant to automotive body-structure applications. This effort requires further developments in the enabling technologies in magnesium extrusion, sheet, high-integrity body casting, joining and assembly as well as the further growth of the knowledge-base in magnesium corrosion protection, crashworthiness, fatigue and durability, and noise, vibration and harshness performance.

Two attributes of this project are particularly significant:

- The focus on a “demonstration structure” as the development object instead of individual components, thereby offering critical subsystem-level capability assessments on technical topics such as joining, corrosion and joining (including multi-material effects) and the performance assessments of vibration, fatigue, overload and possibly energy absorption.
- The establishment of a truly international effort bringing together scientific and engineering expertise in the field of magnesium technology from the United States, Canada and China, in what is believed to be a first-of-its-kind collaboration.

Another key goal of this project is to develop and demonstrate key enabling technologies (e.g. high-integrity body casting, wrought magnesium processing, finishing and joining techniques) and knowledge-base (crashworthiness, noise, vibration and harshness, fatigue and corrosion) for a lightweight magnesium-intensive front-end body structure and other body applications. The Phase II project will design and build a demonstrator (“demo”) structure using the knowledge-base and enabling technologies developed in Phase I. Such “demo” structure is expected to be a paradigm for construction of magnesium-intensive articles, in general, as may be used in automotive or other engineered structures. The demo structure, or its subsidiary features will be tested for corrosion, durability and fatigue performance evaluation. The project also provides a continuing platform for magnesium research collaboration in Canada, China and the United States.

30.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Background:

The Phase I tasks were successfully completed in 2007-2009. Some of the highlights of the Phase I accomplishment include:

- Super-vacuum die-casting technology – weldable body castings (first in the world).
- Low-cost continuous cast magnesium sheet with comparable mechanical properties and formability.
- Optimized extrusion process parameters and process simulation tools (Deform 3D).
- Demonstrated several magnesium and dissimilar metal joining and corrosion protection options – key to automotive applications.
- Significant knowledge-base in magnesium crashworthiness, noise and vibration and fatigue.

The primary goal of this project continues to be the development of key enabling technologies (body casting, extrusion, sheet, finishing and joining) and knowledge-base (crashworthiness, noise, vibration and harshness, durability and corrosion) for primary (load path) body applications of magnesium alloys.

The following are some specific objectives for Phase II which began in 2010:

- Design and analyze a "demo" structure using magnesium casting, extrusion and sheet plus joining and corrosion management technologies developed in Phase I.
- Build and test the "demo" structure for vibration, fatigue, overload and possibly energy absorption.
- Develop robust corrosion and joining strategies acceptable to high-volume, low-cost manufacturing.
- Expand the current knowledge-base in durability (e.g. fatigue), crashworthiness, and noise, vibration and harshness.
- Evaluate three to four improved magnesium alloys for body castings, extrusions, sheet applications.
- Attract high-quality professionals and students, educated in materials science and engineering, to the magnesium R&D infrastructure in Canada, China, and the United States.
- Establish automotive original equipment manufacturer/supplier/academia collaborations in magnesium automotive body or other structural applications.

30.2.1 Computer Modeling Work

- Improved LS-DYNA® modeling for stress, strain and failure especially of vacuum die-cast AM60B. Failure and constitutive modeling.
- Evaluations of four or more LS-DYNA® models comparing analyses to available AM60 component test data. Recommendation on "best" currently available model for vacuum die-cast AM60.
- Independent evaluation of Shenyang, CANMET or ORNL user-defined material models (if developed) in LS-DYNA®.

30.3 Deliverables/Products Developed

- None at this time.

30.4 Technology Transfer Activities

30.4.1 Proprietary Reporting

- Three annual international working meetings will be held in USA (2010), China (2011) and Canada (2012).

30.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

31. Optimization of High-Volume Warm Forming for Lightweight Sheet Alloys (AMD905)

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Project Duration: October 2009 – Present

31.1 Executive Summary

Complex parts such as door inners that can be stamped in mild steel, are difficult or impossible to stamp in aluminum or magnesium using conventional methods. The lower formability of aluminum has led engineers to consider a variety of alternate forming methods including hydroforming, superplastic forming, quick plastic forming, electro-magnetic forming, and warm forming.

Warm forming refers to sheet forming in the temperature range of 200-350°C using heated, matched die sets similar to conventional stamping.

In the previous work (AMD307), a warm forming process was demonstrated using a production grade, commercially-available aluminum alloy AA5182-O. A new cleanable lubricant, suitable for use at warm forming temperatures, was developed and used in all of the forming trials. Two dies were utilized in the project: a production die for the stamping of steel door inners refitted with cartridge heaters and a purpose-built die for warm forming. The second tool, which is a rectangular pan, was designed and built using finite element simulation tools and the thermal distortion behavior knowledge gained during trials with the door inner die. This forming tool was shown to offer exceptional thermal control and minimal distortion as compared to the door inner die. The project AMD602 used the pan die to evaluate the warm forming capability of magnesium sheet and demonstrate a high-volume capable process. Specific accomplishments include:

- Development and demonstration of key elements of warm forming technology with the forming of a door inner panel from a commodity aluminum alloy.
- Application of thermal and forming simulation tools for improved process control in warm forming.
- Design and construction of a new, optimized warm forming die for excellent forming and thermal control.
- Establishment of forming process limits for both commercial aluminum and magnesium sheet materials.
- Development of iso-thermal modeling for finite element prediction of forming and failure during warm forming.
- Development of a fully-automated warm forming cell capable of demonstrating the process under run-at-rate conditions for both aluminum and magnesium.

This project leverages the accomplishments of the previous projects on warm forming to further optimize the process as well as develop equipment designs and simulation tools. The final objective of the project is to demonstrate a

full-scale production process and to identify a supplier-partner for production.

31.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Further optimization of the warm forming process will bring the technology to a implementation ready status and develop a supply base for warm forming. This project will be very important to allow FreedomCAR to meet their goals. Aluminum and magnesium are the only structural metals which can enable significant mass reduction.

The objectives of the project are:

1. Development of a warm forming process that both enhances formability and allows for the use of lower-cost heating methods for the die.
2. Design, build and demonstration of the process developed in on a full-scale door inner panel that is not feasible with conventional stamping.
3. Identification of a production supplier and the design and engineering of a production warm forming process.

The project is divided up into 10 tasks over three phases:

<u>Phase I</u>

Task 1 – Forming trials—Retrofit die from AMD602 to investigate three variants of warm forming which hold promise to further optimize the process for formability, complexity and total cost. Conduct separate forming trials on each of the proposed processes.

Task 2 – Material—Purchase both commodity alloy as well as alloys fabricated from lower-cost processing..

Task 3 – Lubrication—Leverage work on previous warm forming project (AMD307 and AMD602) to develop lower-cost lubricants and application systems. Focus is to move away from boron nitride (BN) containing lubricants to save significant cost.

Task 4 – Phase I report—Report out project deliverables.

<u>Phase II</u>

Task 5 – Die design and build—Apply finite element analysis and design tools developed in previous projects to engineer and build a purpose-built die for forming a full-scale door inner panel. Specific warm forming process will be based on the optimized process developed in Phase I.

Task 6 – Material—Purchase both commodity alloy as well as alloys fabricated from lower-cost processing.

Task 7 – Forming trials—Perform forming trials on scaled-up die system to demonstrate process robustness.

Task 8 – Phase II report—Report out project deliverables.

<u>Phase III</u>

Task 9 – Development of warm forming production process—Partner with supplier to design an automated, production-ready warm forming line including a pre-heat furnace and full automation. Develop cost model of the process in partnership with the supplier to determine production costs.

Task 10 – Report results—Report out project deliverables.

In the last phase of this project the team will partner with a high-volume metal stamper to design and engineer a fully-automated, production warm forming system. The intent of this will be to develop a process capability and production source for warm forming of lightweight alloys as well as develop a cost structure for the production process. The target forming rates will be similar to conventional stamping making the process suitable for even the highest volume applications.

31.3 Deliverables/Products Developed

- The project expects to demonstrate a full-scale production process, and identify a supplier-partner for production.

31.4 Technology Transfer Activities

31.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

31.4.2 Non-Proprietary Publications and Proceedings

[1] DOE Annual Report.

32. Corrosion Inhibiting Electrocoat System for Body-in-White Assemblies (AMD1001)

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Team Members:

- General Motors Company
- Chrysler Group, LLC
- Missouri S&T
- PPG

Project Duration: April 2010 – Present

32.1 Executive Summary

The existing automotive paint line can apply phosphate conversion coating onto cold-rolled steel, galvanized steel, and aluminum alloy mixed-metals body assembly (body-in-white) in the same phosphating tank. After phosphating, the autobodies receive at least four more coating layers (electrocoat, surface primer, base coat and clear coat) to provide corrosion protection and color finishes. Magnesium alloys, due to its favorable strength-to-weight ratio and ease of fabrication, have seen steady increase in use as automotive materials. However, the existing paint line process cannot treat magnesium parts because magnesium is highly reactive in aqueous solutions and galvanic corrosion that occurs when magnesium is coupled with other automotive materials (cold-rolled steel, galvanized steel, and aluminum alloy) is of great concern. The existing phosphating bath is acidic and will dissolve magnesium alloys but does not form a protective magnesium phosphate coating. Also, due to the presence of dissolved magnesium ions in the bath, the phosphate coatings formed on the mixed metal surfaces will be of poor quality. Possible pretreatment and coating schemes to mitigate these undesirable effects include conversion coatings, polymer infiltrates, silicon-based materials, electrophoretic ceramic coatings, anodizing, and post-process baking. However, all these aforementioned technologies will require either pre-treating magnesium parts off-line or committing major capital expenditures to modify the existing automotive paint line.

A typical finishing system for magnesium alloy consists of a pretreatment coating and polymer topcoats. The pretreatment and polymer topcoats have separate functions, with the conversion coating pretreatment chemically reacting with the magnesium substrate while the topcoat is a moisture barrier that may be deposited by a e-coat or powder process.

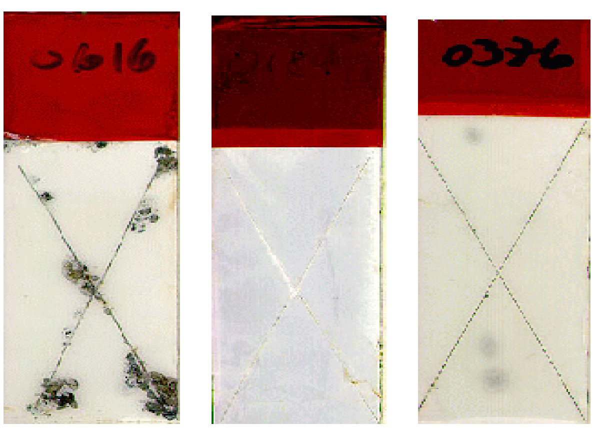
The current corrosion protection mechanism for the existing coating system is based more on physical separation of the active components in corrosion, in particular the electrolyte, rather than active corrosion protection in the presence of an electrolyte, which is the case for galvanized steel. In large part this is due to anodic behavior of the magnesium alloys which are very difficult to electrochemically protect from corrosion. However, if an active protection method can be devised this would enable even wider use of magnesium for automotive applications.

32.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

This project leverages and extends patented corrosion inhibiting e-coating technology on inorganic conversion coatings developed for aluminum-based aerospace structures to dissimilar metal body-in-white vehicles. Incorporation of active, corrosion inhibiting rare-earth compounds into the e-coat system will combine active and barrier passivation technology that is not currently used in the industry. This approach has been shown to be effective for inhomogeneous aluminum alloys that contain second phase intermetallic compounds that form galvanic couples with the aluminum matrix that lead to corrosion in halide containing environments.

Shown in Figure 32-1 are images of aluminum 2024-T3 test panels after 2,000 hours of ASTM B117 salt spray testing showing the improvement in corrosion protection (i.e. lack of salting in the scribe), that is possible by incorporating rare-earth corrosion inhibitors, in this case cerium into the electrocoat bath.

By analogy, high-strength aluminum alloys are similar to body-in-white assemblies in that they contain dissimilar metals components that set up galvanic couples which promote corrosion. To address this situation, rare-earth based conversion coatings have been shown to be effective at mitigating corrosion of metallic substrates. Recent collaboration by GM R&D and Missouri S&T have demonstrated that cerium-based conversion coatings (CeCCs) on Mg AZ91D alloy substrates is effective at

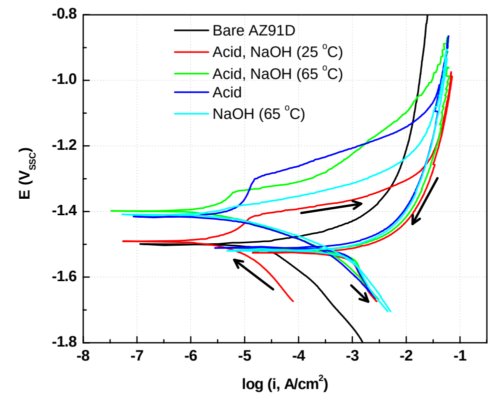


(a) (b) (c)

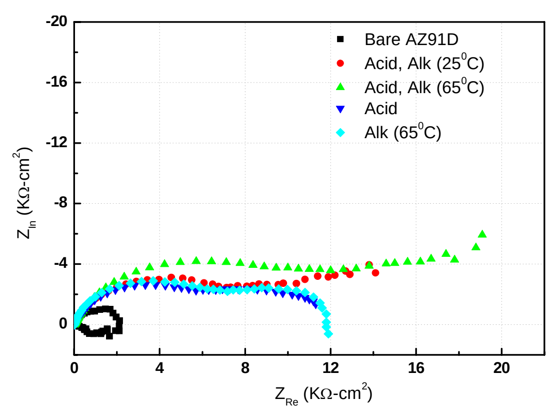
Figure 32-1. Images of e-Coated 2024-T3 Aluminum Panels After Salt Spray Testing; (a) no conversion coating, no corrosion inhibitors in e-coat;(b) chromate conversion coating, no corrosion inhibitors in e-coat; (c) chromate conversion coating, cerium corrosion inhibitors in e-coat

retarding corrosion of the magnesium during exposure to ASTM B117 salt spray testing. Potentiodynamic polarization and electrochemical impedance spectroscopy of AZ91D alloy panels with CeCCs indicated that significant improvements in passivation and impedance resistance were realized with CeCCs. However, the coating passivation and impedance resistance was dependent on processing conditions such as cleaning prior to deposition (Figure 32-2). This work will serve as a starting point for the proposed corrosion coating development effort.

The overall goal is to develop a phosphate replacement conversion bath that can pre-treat



(a)



(b)

Figure 32-2. (a) Cyclic Potentiodynamic Polarization Behavior, and (b) Impedance Spectrum for Bare and Cerium Coated AZ91D Alloy Panels with Different Pre-treatments mixed-metals body-in-white (including magnesium parts) and be compatible with the existing e-coat bath:

- Body-in-white is cleaned through spray clean/dip clean/rinse stages. The proposed process eliminates the phosphate stages including the titanium activator pre-dip tank, the phosphating and dip-rinse tanks, and the post-treatment sealing rinse tank. Initial trials will investigate a simplified conversion coating step that eliminates the pre-dip and post-treatment tanks.
- The pretreated body-in-white would then be coated with a conventional electrocoat.

The stretch goal is to combine conversion coating and e-coating into one corrosion inhibiting e-coat bath with good adhesion and corrosion protection properties.

The project will be executed as three tasks:

1. Set-up a laboratory scale inorganic conversion and e-coating deposition system capable of co-depositing inorganic additives from the electrolyte on magnesium (AZ91D, AM60B, AZ31B), aluminum (AA6016, AA6111), steel (galvanize, cold-rolled), and binary couples (magnesium-aluminum, magnesium-steel, aluminum-steel) substrates. Several methods of joining substrates will be evaluated. Coating characterization and corrosion performance will be evaluated.

2. Demonstrate conversion coatings technology from Task I with e-coat process and formulation on individual and binary couple alloys. Evaluate the adhesion strength and corrosion inhibition of new pretreatment and conventional electrocoat system on magnesium, aluminum, steel and binary coupled alloys (magnesium-aluminum, magnesium-steel, aluminum-steel) substrates. Several methods of joining substrates will be evaluated.

3. Develop a cathodic e-coating process capable of simultaneously co-depositing corrosion inhibiting/adhesion promoter compounds along with the epoxy-based polymer on magnesium, aluminum, steel and various couple combinations, such as binary couples (magnesium-aluminum, magnesium-steel, aluminum-steel) and tertiary couple (magnesium-aluminum-steel) combinations. Several methods of joining substrates will be evaluated. Deposition characteristics, adhesion strength and corrosion inhibition will be evaluated.

32.3 Deliverables/Products Developed

- The project expects to develop a new conversion coating process (cerium-based, zirconium-based, etc.) that can coat magnesium, aluminum, zinc, steel mixed-metals; combining conversion coatings and e-coating into one step coating process (stretch goal).

32.4 Technology Transfer Activities

32.4.1 Proprietary Reporting

- AMD Offsite talks and Semi-Annual Reports to DOE.

32.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

33. Advanced Planning: Exploratory Evaluation and Formulation of Projects in Lightweight Material Technology and Processes (AMP999)

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Team Members:

- Ford Motor Company
- General Motors Corporation
- DaimlerChrysler Corporation

Project Duration: April 1999 – Present

33.1 Executive Summary

The purpose of this planning "project" is to perform preliminary evaluation of technical concepts in materials and/or processes to evaluate and determine which projects appear to have the greatest potential and warrant inclusion in the USAMP Cooperative Agreement portfolio as an independent full-scale study. The intent is to minimize the initiation of fully funded projects that may prove to be unsuccessful. Although success is never ensured with any research and development project, the efforts concentrated in this preliminary effort are expected to prove beneficial and result in a cost savings to the government and the USAMP.

33.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objective of this project is to provide industry representatives with a means to formulate Lightweight Material project proposals based upon performing preliminary evaluation of technological concepts in materials, and/or processes which appear to have significant potential for increasing the use of lightweight materials in vehicles. Evaluations will include assessing the feasibility and desirability of developing the technology for high-volume automobile production, through such methods as preliminary cost studies, technology demonstrations etc.

Numerous projects have resulted from needs assessments, plans and evaluation developed under this project.

The following activities are currently under consideration/development for establishing large-scale research programs:

- Ultrasonic Spot Welding of Magnesium – Feasibility Assessment.
- Corrosion Inhibiting Electrocoat System for Body-in-White Assemblies.
- Optimize alternative Casting Methods Developed in AMD601 (HIMAC) for Higher-Strength Magnesium Alloys.
- Body and Chassis Design with Thin Gauge AHSS and UHSS Steels.
- Formability Evaluation of Emerging Generation 3 AHSS Products.
- Hollow Shafts for Weight Reduction and Optimal Performance.
- Product/Process Guidelines for Quench and Partition (Q&P) Steel Generation 3 AHSS.

Project Activities 1999 to Present:

Industry representatives met to formulate and refine project concepts before initiating the projects.

Problems Encountered:

No technical problems were encountered. The greatest difficulty was in having industry representatives record their efforts in support of this activity. Because these discussions often involve people that are not involved in other USAMP or USCAR activities, they are unaccustomed to formally recording their time. Also, many often view the time investment as relatively minor, and therefore, they are unwilling to accept the burden of recording their time. Thus, much of the time spent in this effort is unreported.

Conclusions:

This project evaluation approach has led to the formation of significantly formed USAMP projects. Project direction, content, milestones are more clearly defined and supported than was the case previously, when projects were adopted based on a more general description of content and direction.

Based upon previous successful identification and implementation of numerous projects, we anticipate using this method of developing new projects for the foreseeable future.

33.3 Deliverables/Products Developed

No products are expected nor developed by this project.

33.4 Technology Transfer Activities

33.4.1 Proprietary Reporting

- Tech transfer is left to the projects that result from these planning activities.

33.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

34. Design and Product Optimization for Cast Light Metals (LMD110)

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Team Members:

- Ford Motor Company
- General Motors Corporation
- DaimlerChrysler Corporation
- The Aluminum Association
- Oak Ridge National Lab (ORNL)
- Lawrence Livermore National Lab (LLNL)
- 32 companies from the casting supply base
- Independent testing research labs
- American Foundrymen's Society
- Sandia National Lab (SNL)

Project Duration: April 1995 – 2009

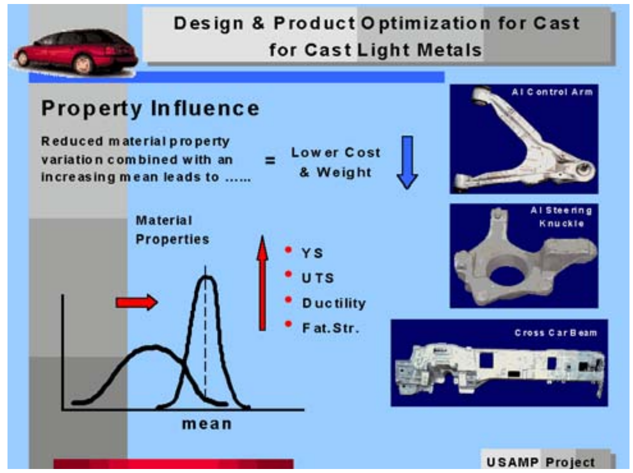

Figure 34-1. Technology Developed to Assist Engineers and Product Designers Reduce Cost and Component Variation, thereby Yielding Lower Component Cost and Weight

34.1 Executive Summary

The goal of the Cast Light Metals (CLM) project was to develop information and technology for the U.S. automotive industry that would optimize design and improve product capabilities for lightweight, high-strength, cast structural aluminum and magnesium components that will then be used for chassis and interior automotive uses. The details and deliverables of this project are shown in Figure 34-1.

34.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The major details/deliverables of the CLM project were completed on schedule (April 15, 2000 for the CRADA activities). However, the Cooperative Agreement activities of the project were extended until December 31, 2000 to include the results from the redesigned and optimized mule casting and also, several production sensor tests being completed by LLNL. The completion of both of these items provided significant proof of the validity of the project team's accomplishments.

The project accomplishments are listed below:

1. *Development of a cast light metal material design property database*—The generated database uses an entirely different architecture for comparing aluminum and magnesium. It includes historical literature data; comprehensive mechanical property data derived from samples excised from actual production aluminum chassis castings. Casting processes examined include: aluminum – squeeze casting, semi-solid forming, gravity pour, low pressure, tilt pour and VRC/PRC process; magnesium – high-pressure die-casting.

2. *Publication of design rules/guidelines and component evaluation methodologies*—A new design guideline was developed for the design of cast light metal structural components. It incorporated learnings from successful applications, property database information and industry input.

3. *Development of on-line process monitoring, feedback control, and non-destructive evaluation technique(s) to assure cast component consistency and quality*—LLNL adapted (and applied) rapid response temperature optical sensors for process monitoring of two production casting facilities, and the results were included in the final report. LLNL had evaluated quality assurance methodologies/equipment and developed a new radioscopic standard for castings based on improving existing ASTM standards.

4. *Evaluation and development of numerical modeling techniques to predict cast micro-structure and subsequent mechanical properties throughout cast component sections*—One of the major goals (and accomplishments) of the project was to develop math-based models that would predict the microstructure and subsequently the mechanical (tensile and cyclic) properties of cast components from the mold, casting and component function criteria. The results of this work was a joint effort of industry participants, national labs and academia.

    - Microstructure Studies: The study of variability in ductility and UTS of seven groups of production casting of A356.0 alloy and one group of AM60 alloy was completed. These samples were successfully correlated to the presence of defects through careful qualitative and quantitative fractographic observations and quantitative microstructural data obtained through digital image analysis and stereological techniques. Quantitative correlation between tensile elongation and total area fraction of defects (oxides, pores, flux residues, etc.) of the fracture surface has been demonstrated for various groups of production castings studied so far. Fractographic analysis work of the tensile test specimens of AM60 magnesium-alloy specimens from an instrument panel (Group E) was completed. This information was completed by Georgia Tech and was useful for the modeling work done by ORNL and SNL.

5. *Optimization of production rear lower control arm*—The CLM Team undertook the task of incorporating all of the project findings into the optimization of the mule casting (Figure 34-2), which was (and still is) a production cast aluminum A-365 rear lower control arm. The application of the modeling work done by ORNL and SNL into existing commercial codes was used for optimizing the part – prior to the development of new tooling. A new part, slightly re-designed (with reduced weight) was cast in one of the participating production casting facilities and tested. Figure 34-3 is a plot of the load-displacement curve comparing:

    - The aluminum production control arm (painted black that was converted from gray iron to aluminum).

The same configuration of the control arm (painted grey) that was cast at DaimlerChrysler facility (not a production control arm).

- Two identical experiments with the new optimized-reduced weight aluminum (non-production control arm).

The plot clearly shows, that the new optimized-reduced-weight aluminum control arm has approximately 50% more load bearing capacity than the current aluminum production casting. The test was repeated for verification. The fixture location was in the same spot as the previous ones.

Computer modeling—A synergistic program that included experiments, micromechanical finite element modeling of local microstructures, and macroscale modeling of the micro-structure-property relations of fatigue gave definite results for optimizing the design of structural cast components. The project team

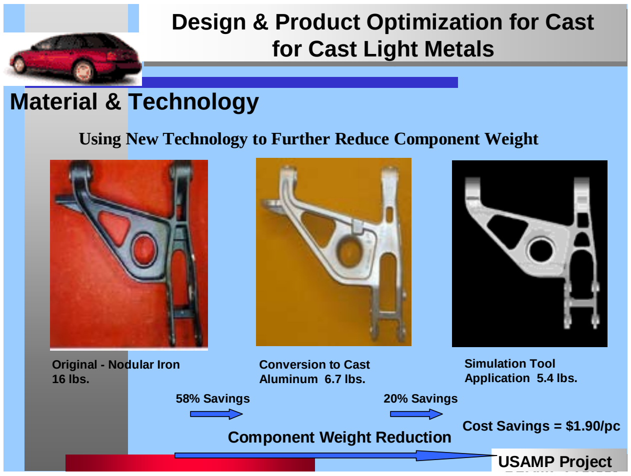

Figure 34-2. Evolution of the Rear Lower Control Arm

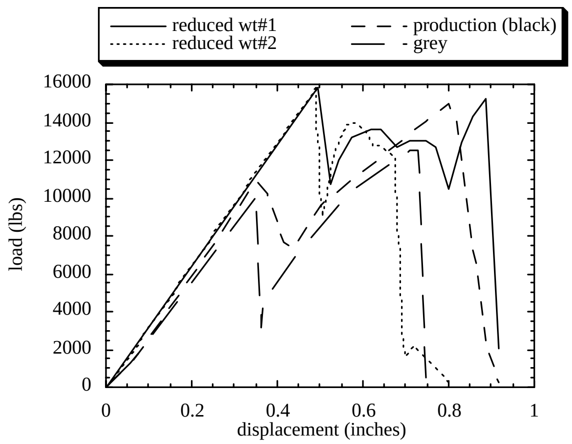

Figure 34-3. Plot of Load-Displacement Curve Comparisons

developed relations that contained explicit treatment of each inclusion type in order to offer a link between quantitative characterization of inclusion populations and fatigue life estimates, including the variability of fatigue life. Such relations provide a link in foundries to help guide the selection of section thickness, impurity and gas level controls, solidification which have been developing the ORNL part of the CLM project. This modeling effort was successful. An increase in load carry (50%) was exhibited with the optimized, lightweight design (25% lighter) and the fatigue life was lengthened.

34.3 Deliverables/Products Developed

- Design and Optimization for Cast for Cast Light Metals.

34.4 Technology Transfer Activities

34.4.1 Proprietary Reporting

- The technical information (with the distribution of the final report) was transferred to all of the CLM project participants, the Big 3 and government support teams. This report included all of the publications by the project investigators.
- A project newsletter (*Cast Light Metal News*) was published monthly, that updated all project participants.
- Quarterly review meetings (four times per year) were held at various locations throughout the U.S.

34.4.2 Non-Proprietary Publications and Proceedings

[1] Arrangements have been made through the offices of the American Foundry Society (AFS), where copies of the reports can be obtained through AFS' web site.

1. Enhanced Forming Limit Curve Effect (ASP040)

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Team Members:

- Bethlehem Steel Corporation
- Daimler Chrysler Corporation
- Dofasco, Inc.
- Ford Motor Company
- General Motors Corporation
- Keeler Technologies
- BS Levy Consultants
- IWERK.com
- Ispat Inland, Inc.
- National Steel Corporation
- Rouge Steel Company
- Stelco, Inc.
- U.S. Steel Corporation

Project Duration: 1997 – 2001

1.1 Executive Summary

The Enhanced Formability Project was initiated on the basis of press shop observations that parts with strains substantially in excess of conventional as-received forming limit curves (FLCs) could be successfully produced in large volume without breakage. In these cases, the apparent increase in the as-received FLC was observed in areas of the part that had been subjected to bending and unbending through drawbeads as steel sheet moved off a binder. If advantage could be taken of this additional formability, higher quality panels could be produced and die modifications during press shop try-out would be reduced. This required experimental work to quantify the increase in FLCs due to bending and unbending and to provide some mechanistic basis for this behavior. This increase in an FLC after bending and unbending was described as the enhanced FLC effect, which was represented by ΔFLC_0.

An experimental concept for quantifying the enhanced FLC effect is based on the design and construction of a channel draw die, which produced parts large enough for subsequent experimental determination of FLCs. The tooling radii and drawbead penetration primarily controlled the magnitudes of the bending and unbending strains. To increase the range of bending and unbending strains, an outboard bead system was designed to generate different degrees of back tension.

The research project generated predictive equations for use in the press shops and to provide a mechanistic basis for understanding the enhanced FLC effect. The extensive Research Report and two data CD's containing all the details and data of the multi-year research program are located on the Auto/Steel Partnership's web site, www.a-sp.org.

The final phase of the program was to translate the research work into procedures applicable to press shop functions, such as die try-out, process monitoring, and finite element analysis design of parts. The deliverables of this closing phase were a Technology Report and an in-plant training program.

Explaining an enhanced FLC concept to the press shops would be difficult because the research indicates that deformation and thinning of the metal going through the beads creates increased stretching limits. However, the enhanced FLC measured by ΔFLC_0 is a result of the chosen experimental program. Within the stamping the FLC is not enhanced, but remains a constant to be used for all areas of the stamping

The key to press shop application is that thinning strains created by the bending and unbending deformation through beads or over tight punch and die radii are only 40% as damaging in terms of forming severity as

uniform thinning caused by metal stretching. Thus, a Bead Correction Factor (BCF) can be applied to correct strains measured on metal exiting the bend and unbend zone before plotting them on the FLC.

1.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project objective was developing quantitative relationships for predicting the enhanced FLC effect. Considerable effort was devoted to determining the experimental variability of all measured quantities used in its prediction. This information is used to evaluate the reliability of the predictive equations.

With the basic experimental approach determined, several experimental methods were developed to obtain the needed data quality.

Development of a more accurate system for determining FLCs – Design and construction of a channel draw die which produced parts large enough for subsequent experimental determination of FLCs (Figure 1-1).

Increase the range of bending and unbending strains – Outboard bead system was designed to generate different degrees of back tension. A hydraulic cylinder with a load cell was added as an auxiliary to the channel draw die.

Development of an experimental method for determining actual bending radius – In-situ system for measuring the actual radii in drawbeads was developed.

Provide a mechanistic basis for understanding the enhanced FLC effect – Predictive equations were generated for use in the press shops.

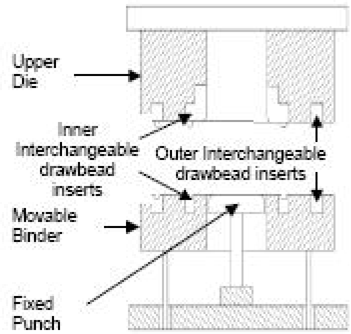

Figure 1-1. Schematic of the Research Channel Draw Die Showing Location of Interchangeable Draw Beads

Translate the research work into procedures applicable to press shop functions - Deliverables of the closing phase are a Technology Report and an in-plant training program.

Problems Encountered:

- Determining actual bending radius was more difficult than anticipated. Initial attempts to measure radii from the channel draw test pieces provided accurate measurements, but it was not possible to account for springback. As a result, considerable work was done to successfully develop an in-situ system for measuring the actual radii in drawbeads.
- Explaining an enhanced FLC concept to the press shops would be difficult because the research indicates that deformation and thinning of the metal going through the beads creates increased stretching limits. However, the enhanced FLC measured by ΔFLC_0 is a result of the chosen experimental project. Within the stamping the FLC is not enhanced, but remains a constant to be used for all areas of the stamping.

1.3 Deliverables/Products Developed

- Technology report.
- Curriculum for in-plant training.

1.4 Technology Transfer Activities

1.4.1 Proprietary Reporting

- Report on "Procedure for Determining the Forming Limit Diagram for HSS600-1.2mm," contracted to Industrial Research & Development Institute (IRDI).
- Annual Auto/Steel Partnership Technical Communications Meeting, Auburn Hills, MI, February 22, 2001.
- An extensive Research Report *Enhanced Forming Limit Diagram –Project Team Research Report (5)* written by B. Levy and D. Green is available on the Auto/Steel Partnership web site at www.a-sp.org.
- Two CDs containing spreadsheets and drawbead deformation videos are available on the Auto/Steel Partnership web site at www.a-sp.org.
- The training manual, entitled *The Bead Correction Factor (7),* is available on the Auto/Steel Partnership web site at www.a-sp.org.

1.4.2 Non-Proprietary Publications and Proceedings

[1] Green, D., "An Experimental Technique to Determine the Behavior of Sheet Metal in a Drawbead," Society of Automotive Engineers, SAE 2001-01-11360.

[2] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

2. Advanced High-Strength Steel Stamping Project (ASP050)

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- DaimlerChrysler Corporation
- Auto/Steel Partnership
- Rouge Steel Company
- United States Steel Corporation
- Ronart Industries
- Dofasco, Inc.
- Ispat Inland, Inc.
- Stelco, Inc.

Project Duration: January 2001 – Present

2.1 Executive Summary

Due to the unique mechanical properties of high-strength steel (HSS), achieving dimensional accuracy after forming has been difficult, resulting in delays for die construction and try-out. This research project is directed towards the development of product design and manufacturing process guidelines to overcome the problems related to the stamping of dimensionally accurate HSS and advanced high-strength steel (AHSS) automotive sheet metal components.

Computer simulation technology has been widely applied in the stamping industry and has been recognized as a virtual stamping tool to anticipate and identify formability issues, such as splits and buckles. It can also be used to evaluate solutions before the actual stamping dies are made. However, experience has demonstrated that computer simulation has not been reliable in predicting the degree or modes of springback. Because the actual dimensions of HSS and AHSS stampings are somewhat unpredictable with current springback simulation technology, corrective die face machining requirements may be four to six times that expected for mild steel applications and typically result in two to three months of added die try-out time.

The HSS Stamping Project Group is approaching this problem in two ways: improving prediction by computer simulation and springback control by corrective process planning. The Simulation Project Group is working to improve the finite element analysis predictive accuracy to determine die processes and press parameters that produce the least amount of springback. Springback control experiments have been conducted using tooling designed to replicate actual production stamping die processes. These experiments have confirmed the importance of optimizing both the part geometry and the stamping process in order to reduce residual stress, flange springback and part-to-part variation. Stamped parts were measured and data was recorded and analyzed. This empirical data is used to improve predictive capabilities and manufacturing process planning. AHSS structural components of the Auto/Steel Partnership Lightweight Front-End project and lightweight sheet metal designs in general will benefit from this research.

2.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Objectives:

- Evaluate springback prediction capability.
- Investigate die processes and part features for best part quality in AHSS.
  - Minimum springback/curl/twist.
  - Minimum wrinkling.
  - Dimensional accuracy.

- Assess the impact of AHSS on press force/energy requirements.
- Support development of product/process design guidelines and failure criteria for AHSS.
- Provide for effective technology transfer.

Process Simulation – To develop and provide comprehensive sets of tooling and part math data to support computer simulations of various stamping processes. The information is used to determine the ability to predict formability and fracture, as well as the dimensional control effects of these processes on AHSS sheet metal.

- This activity carefully defined and executed experiments to provide comprehensive sets of tooling and part math data for supporting evaluation of computer simulations of various die processes and AHSS sheet steels. An effort was started to understand and predict fracture in these materials. These efforts will result in an accurate assessment of feasibility, reduced tooling lead time, and attainment of required levels of part quality.

Springback Control – To support ongoing studies of die process methods and develop part design geometries that will minimize or eliminate springback and springback variation resulting in commercially acceptable dimensional performance with minimum try-out.

- The activity expanded on current knowledge and experience with AHSS in order to provide information and case studies in support of product and process guidelines for high priority parts manufactured from various AHSS steel grades for use by product designers and die process planners (e.g. B-pillar).

Shear Fracture – To evaluate fracture characteristics of AHSS products, for the purpose of influencing material specifications and development of failure criteria in stamping.

2.2.1 Computer Modeling Work

- Pam-Stamp, LS-DYNA®, ABACUS, etc. commercialization simulation softwares were used. Several finite element modeling simulation reports by Dr. Du can be found on the Auto/Steel Partnership website (www.a-sp.org)

2.3 Deliverables/Products Developed

- Comprehensive set of tooling and part math data to support computer simulations of various stamping processes.
- Reports on Edge Cracking Criteria and Shear Fracture Guidelines.

2.4 Technology Transfer Activities

2.4.1 Proprietary Reporting

- Annual Auto/Steel Partnership Technical Communications Meetings, Auburn Hills, MI, February 22, 2001 and October 6, 2010.
- Presented Stamping Guidelines to Original Equipment Manufacturers and Supplier Groups.
- Measurement database of all springback control stampings, published by GKS Inspection Services, Inc.

2.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org (under publications/formability).

[2] Project results related to shear fracture and edge cracking have been reported at:

– Great Designs in Steel, May 2010.

- IDDRG-NADDRG Conferences, June 2009.
- Technical sessions in SAE, April 2010.
- AHSS Fracture Symposium, August 2010, MIT.

3. Tube Hydroforming Materials and Lubricants (ASP060)

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- General Motors Corporation
- DaimlerChrysler Corporation
- Auto/Steel Partnership
- Industrial Research & Development Institute (IRDI)
- Rouge Steel Company
- United States Steel Corporation
- Ispat Inland, Inc.
- CANMET
- Schuler
- Dofasco, Inc.
- Stelco, Inc.

Project Duration: January 2001 – January 2011

3.1 Executive Summary

Over the past twelve years the Auto/Steel Partnership (A/SP) Tube Hydroforming Materials and Lubricants team has been conducting projects to aid the implementation of tubular hydroforming in automotive applications. The approach taken has been to initially gain a basic understanding of the hydroforming process and potential issues and to then extend learning to real world applications of increasing complexity.

Presently, the formability limits for steel in tubular hydroforming are poorly understood. Practitioners are using the sheet steel forming limits developed for conventional stamping processes to assess the formability of hydroformed components. For example, the effect of axial compression on the forming limits of steel is unknown. Also, the effect of prior strain induced in the tube conversion and tube bending processes that precede the hydroforming operation have been ignored. Part accuracy needs to be assessed and improved to allow optimum application in the lightweighting of vehicles.

In addition, the tests that tube producers are using to evaluate tube quality do not properly address metal forming issues relevant to tubular hydroforming. The current tests focus on weld quality and dimensional accuracy of the tubes but do not adequately describe the amount of ductility left in the tube for post-forming operations, such as hydroforming. There is a need to develop and validate tube-testing methods that are suitable for evaluating and comparing material formability, and are also suitable for input into finite element models.

Furthermore, more information is needed on the fundamental material attributes that control the hydroformability limits of steel. This knowledge will allow steelmakers to develop appropriate new steel grades or appropriately apply existing steel grades to hydroforming applications. Experiments have been conducted using the facilities of the IRDI of Midland, Ontario, Canada and the CANMET Materials Technology Laboratory of Ottawa, Ontario, Canada.

3.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The overall goal of this project is to identify and overcome the design, manufacturing and material barriers for the use of sheet steel from mild to advanced high-strength steel (AHSS) when applied to automotive tubular hydroforming applications.

Key objectives include:

- Develop mechanical test procedures and forming limit diagrams (FLDs) for tubes.
- Improve accuracy and confidence in finite element modeling (FEM) 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 FEM.
- Develop an improved understanding of the structural and cost benefits of hydroformed components.
- Support the work of other A/SP project teams when they investigate hydroformed structural components.
- Validate the performance benefits of hydroforming in automotive structures.
- Facilitate the adoption of cutting-edge hydroforming applications (AHSS TWTs) in vehicle structures.

<u>Status</u>:

- Testing procedures to obtain representative mechanical properties of tubes. (Complete)
- FLD for tube hydroforming. (Complete)
- Study the influence of lubricants and the tube bending process on subsequent hydroforming operations.
  - Initial project and web-based “html” report. (Complete)
  - Re-writes of FLD and influence of bending on hydroforming reports in “conventional” research report format, PowerPoint presentations and CDs prepared for technology transfer. (Complete)
  - Additional outside and inside corner fill testing of 90° bent interstitial-free (IF) and DP600 tubes with welded-end caps experiments and report. (Complete)
- Preliminary study on the forming characteristics of TWTs.
  - Hydroforming experiments and report. (Complete)
- Fabricate AHSS hydroform TWT lightweight front rails (LWFES concept).
  - Completed September 30, 2006.
  - Steels delivered to Soudronic in Switzerland for making TWTs. (Successfully completed in February 2007 after overcoming significant manufacturing problems).
  - Schuler Hydroforming subcontracted hydroform tool build (Complete – August 2006).
  - CNC rotary draw tube bending of TWT performs subcontracted by Schuler to Erin Industries. (Success experienced in April 2008 after overcoming significant splitting and wrinkling on tension and compression sides of tube bends respectively).
  - Hydroform prototype trials at Schuler have been unsuccessful to date. Tube sealing and tube collapse issues have appear to have been overcome with the use of welded end caps, but tube pinching problems leading to premature failure; now need to be solved.
- Investigation of fabricating dual-phase and TRIP steel tube from an ERW production line.
  - Project was awarded to CANMET using their laboratory tube high-frequency induction tube welding draw bench.

  - Steels (DP780, TRIP780, HSLA350) supplied to CANMET (February 2008).
  - All high-frequency induction tube seam welding experiments comprising the design of experiments (DoE) were completed (November 2008).
  - Characterization testing and analysis completed (January 2009).
  - Final report delivered to the A/SP Hydroform team (February 2009).
- Comparing laser-welded DP and TRIP steels with ERW tubes of same materials.
  - Project task was deleted due to A/SP budget constraints.
- Stress and strain measurements under non-linear loading through tube fracture for improved modeling and prediction.
  - Project was transferred to a newly-formed A/SP project team (November 2008).

3.3 Deliverables/Products Developed

- Hydroformed front rail components.

3.4 Technology Transfer Activities

3.4.1 Proprietary Reporting

- Annual Auto/Steel Partnership Technical Communications Meeting, Auburn Hills, MI, February 22, 2001.
- “Hydroforming Group,” Auto/Steel Partnership Program Review, Department of Energy, September 21, 2005.
- “Hydroforming Committee,” A-S/P SPARC Financial Planning Review, July 18, 2006.

3.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org (under publications/hydroforming).

[2] Soldaat, R. et al., “Results of Auto/Steel Partnership (A/SP) Steel Tube Hydroforming Materials and Lubricants Experimental Projects,” SAE Technical Paper #2009-01-1390, SAE 2009 World Congress, Detroit, MI, April 20, 2009.

4. Non-Linear Strain Paths (ASP061)

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- DaimlerChrysler Corporation
- LSTC
- Oakland University
- Wayne State University
- ArcelorMittal
- U.S. Steel
- Severstal
- NCMS

Project Duration: October 2009 – Present

4.1 Executive Summary

Existing constitutive models useful for the simulation of metal deformation processes fall into two distinct classes, one class based on isotropic hardening and applicable with a reasonable validated accuracy to processes dominated by linear monotonic loading; and the other class based on mixed isotropic-kinematic hardening and applicable with a reasonable validated accuracy to processes dominated by linear monotonic or cycle loading. However, sparse data published in the existing literature show that significant discrepancies between prediction and reality may be expected due to effects that arise under non-linear loading that are not present or not detectable in linear deformation processes.

The non-linear strain path deformation carries a material through the manufacturing process from a sheet blank to stamping and bake-oven hardening until a vehicle performance event such as a crash. Consequently, the steel parts do not respond the same way as if they were still virgin materials due to the strain-hardening and bake-hardening of the material and non-uniform thickness distribution which resulted from forming. Furthermore, the deformation paths will generally have abrupt changes from that during stamping. It is thus critical to incorporate the prior manufacturing effects such as forming and bake-hardening into product performance simulations with reliable constitutive and fracture models.

The project aims to deliver a comprehensive set of experimental data and associated predictive models for several advanced high-strength steels (AHSS) under non-linear strain path deformations. It will enable efficient vehicle design for more weight reduction opportunities to take advantage of the rapid hardening behavior of AHSS, and accelerate AHSS usage by reducing the cost and time for AHSS product design and manufacturing.

4.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objectives of this project are to:

1. Develop, validate and implement anisotropic constitutive models, path-independent forming limit and fracture criteria, and anisotropic bake-hardening models for AHSS through extensive testing and model correlation under non-linear strain paths.
    - Extensive tensile testing of ASTM E9 specimens using digital image correlation (DIC) initiated at Oakland University.
    - Temperature-dependence of strain path experiments initiated at Wayne State University.

2. Demonstrate and quantify weight-saving potentials for the design concept of incorporating non-linear strain paths in vehicle manufacturing into vehicle performance attribute predictions.

The project team has initiated the key tasks as follows (with status summarized):

1. Transient Hardening Behavior and Models under Non-linear Strain Paths.
2. Forming Limits and Fracture Behavior under Non-linear Strain Paths.
3. Orientation-Dependent Bake-Hardening Behavior for Dual-Phase and Bake-Hardenable Steels.
4. Technology Demonstration for Weight Reduction Potentials.

3. A consensus technical specification for application of digital image correlation (DIC) in non-linear tensile strain measurement was developed by the team in March 2010 to solicit DIC vendor quotes. Oakland University was contracted to provide DIC test services and Wayne State University to perform temperature-dependent strain testing experiments on AHSS grades.

4.2.1 Computer Modeling Work

Tasks under Objective 1 will address this in addition to extensive FEM simulation support of non-linear strain tests provided by LSTC.

4.3 Deliverables/Products Developed

- None at this time as material testing was initiated in July 2010. Comprehensive database and material models are expected upon project conclusion.

4.4 Technology Transfer Activities

4.4.1 Proprietary Reporting

- USAMP and A/SP Offsite presentations in 2009 and 2010.

4.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

5. Joining Technologies (ASP070)

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- Auto/Steel Partnership
- Ispat Inland
- Dolfi AWS, LLC
- Dofasco, Inc.
- United States Steel Corporation
- Edison Welding Institute (EWI)
- RoMan Engineering Services, Inc.
- University of Toledo

Project Duration: October 2001 – Present

5.1 Executive Summary

Knowledge gained from Auto/Steel Partnership (A/SP) sponsored welding tasks has successfully been applied to a number of A/SP lightweighting projects such as, fabricating a Lightweight Front-End Structure using conventional body-shop welding equipment. Impact and fatigue performance of welded and weld-bonded assemblies has been completed for several grades of AHSS material. A document for spot weld quality acceptance was developed for use as an automotive industry standard. The team has evaluated joining processes such as MIG (metal inert gas), laser, plasma-assisted MIG welding, mechanical clinching, friction stir spot welding, and fracture toughened adhesive welding and joining of advanced high-strength steel (AHSS).

The ultimate goal for this project is to remove barriers for application of AHSS to allow automotive manufacturers to reduce weight and enhance body-in-white performance and to provide welding parameters and joint performance data for future applications of AHSS.

5.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objective of the High-Strength Steel Joining Technologies project team is to provide welding and joining expertise to the A/SP lightweighting projects to facilitate the increased use of 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.

Accomplishments:

- Completed first two ballots of an American National Standard describing test methods to evaluate the welding behavior of automotive sheet steel (ANSI/AWS D8.9.201X)
- Completed joint efficiency study (Phase I to III) for process cost comparisons resulting in a software that would allow users to compare the manufacturing and business costs of various automotive welding and joining processes to support process selection decisions.
- Initiated in 2010 a design of experiments to screen GMAW (gas-metal arc welding) variables for their significance and effect on weldability characterization process.

5.3 Deliverables/Products Developed

- Publication of a material weldability characterization standard by ANSI.

- A study of AHSS joint efficiency for assembly plant weld repair or substitution.
- Welding and joining application guidelines.
- Weld process finite element modeling.

5.4 Technology Transfer Activities

5.4.1 Proprietary Reporting

- All information and testing is currently held within the Joining Committee and the Auto/Steel Partnership.
- Annual Auto/Steel Partnership Technical Communications Meeting, Auburn Hills, MI, February 22, 2001.
- A/SP Offsite meetings – annual presentations.

5.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

6. Lightweight Door Outer Panel Project (ASP090)

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- Ispat Inland, Inc.
- Severstal NA, Inc.
- Stelco, Inc.
- United States Steel Corporation
- EDAG
- Oxford Automotive

Project Duration: 2000 – 2004

6.1 Executive Summary

The project's goal was to promote the use of advanced high-strength steel (AHSS) for door inner and outer panel applications. In Phase I (2001), the Auto/Steel Partnership (A/SP) completed a Lightweight Closures Project whose objective was to achieve 25% mass reduction on a 2002 DaimlerChrysler Jeep KJ door assembly at a cost penalty of less than $0.70/lb. saved. A multi-piece inner door panel construction was developed which achieved a mass reduction of 3.40 lbs. However, A/SP original equipment manufacturer members rejected the use of a multi-piece inner panel as too sensitive for dimensional control during the fabrication process. Based on this feedback, the A/SP Lightweight Closures Project was redirected to use a single-piece inner panel with alternative design and manufacturing proposals to maximize mass savings. This became the subject of a Phase II initiative.

The Phase II (2002) A/SP Lightweight Closures Project sought to optimize material usage on a single-piece door inner panel using several different technologies. Technologies considered were: 1) multi-piece tailor-welded blanks (TWBs), 2) 2D TWBs, 3) patch blanks and 4) hydroformed substructures. The project maintained its direction toward real-world manufacturing environments reviewing numerous options. Through investigation of manufacturability, performance and their impact on mass, multiple concepts were eliminated in order to focus on selected designs for better in depth studies.

The mass, cost and performance results showed a mass reduction percent of the inner and related reinforcements ranged from 12.5-18.6%. The cost per pound saved was above $1.71/lb. in all cases, which exceeded the $0.70/lb.saved target.

Preliminary analysis on the door outer showed a potential 20% mass reduction at no cost penalty by utilizing AHSS. Therefore, it was recommended that future investigation, Phase III (2004), be focused on AHSS application in the door outer panel.

The direction for the Phase III (2004) A/SP Lightweight Closure projects was the reduction of the door outer panel thickness using AHSS, employing different materials/thicknesses and coating variations. Materials considered for this project were bake-hardenable and dual-phase steels, with electrogalvanized (EG) and hot-dipped galvannealed (HDGA) coatings. Both analytical and physical properties were compared to document the accuracy of actual to analytical results determined upon its material property structure (Figure 6-1).

The project used both, the baseline die configuration and a die configuration, with product and styling concessions. While the baseline door, from the 2002 Jeep Liberty (KJ) used an IFRephos 0.74mm minimum thickness material, which is typical construction for current production small SUV vehicle doors, the project was successful in achieving mass reduction up to 17.2% for the door closure outer panel using:

- BH250 at 0.64mm with a slight styling concession.
- DP500 at gauges as low as 0.62mm with the baseline die design configuration.

The materials used in this project represent good opportunities for weight reduction at near equivalent costs. However, it should be stated that though they may provide equivalent or better dent resistance at thin gauges, a different door design may present a situation where stiffness constraints would prohibit the use of these materials.

6.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The purpose of this project is to investigate the option of using high-strength steel for the door outer panel, as well as investigate mass savings opportunities and evaluate cost impact. The project focused on formability and product performance including research in the following areas:

- Issues: dent resistance, oil canning, panel stiffness, surface quality, etc.
- Material guidelines.
- Formability guidelines.
- Springback, material memory, etc.

Figure 6-1. A/SP Lightweight Door Outer Project Phase III Prototype Door

A detailed investigation of hemming processes for high-strength steels was outside of the scope of this project. Although hemming issues may occur, these issues are not perceived as insurmountable based on member experience with AHSS in a production environment. The impact of high-strength steel on production tooling, as well as weldability issues, also were outside of the scope of this project.

The same baseline vehicle door architecture used for the 2001 and 2002 project design development work, i.e. the 2002 Daimler-Chrysler KJ (Jeep Liberty; Figure 6-2), were also used for this project.

Figure 6-2. Baseline Vehicle, 2002 Jeep Liberty (KJ)

The design development goal is as follows:

- Design Options are to achieve a formable door outer panel without a product change to the baseline door and determining the impact of lower thickness and higher-strength materials on product requirements including:

  - Dent resistance
  - Panel stiffness
  - Palm printing
  - Maximum deflection
  - Oil canning
  - Thinning
  - Overall door performance (sag, check load, etc.).
- Determine the manufacturing limits/requirements for producing a door with a high-strength steel door outer.
  - Stamping (springback, formability)
  - Surface quality
  - Product design considerations (radii, wall angle, etc.)
  - Process Considerations.
- Target a 20% mass reduction over the baseline vehicle door outer panel, using high-strength steels with lower gauges, at zero incremental cost increase or at a cost savings.
  - Minimize recurring and non-recurring cost impact to achieve this reduction
  - Develop applicable "real-world" design outputs
  - Develop applicable "real-world" manufacturing outputs
  - Design for a theoretical SOP 2006
  - Explore product and manufacturing development paths
  - Determine the impact of lower thickness, higher-strength materials on product requirements.

The major scope of this project focused on formability. Hard tools were not built; Kirksite tooling was utilized in the prototype trials to achieve a formable outer door panel.

The A/SP team members agreed that the outer door closure project brought forth very informative data at all levels of this project. While some areas became concerns, others showed positives that may be applied to today's manufacturing guidelines. Forming an AHSS outer panel proved to be a doable option, but still elicited caution due to the surface quality. The particular testing that was done during this project showed a positive improvement but additional testing would provide a complete picture of the true overall limitations of the materials in regards to door closures. The geometric revisions (10A and 11A) to aid in the forming of the outer doors were determined through this project and possible limitation guidelines documented.

This project became a positive foundation for future development programs to further aid in the use of high-strength steel at thinner gauges to help in mass reduction for outer door panels.

The weight savings were significant and came close to meeting the 20% target. The savings varied from door-to-door, but were significant enough overall to warrant further investigation for production development. The forming of the door outer panel with the existing baseline design became a plus for this project.

The physical test results on the prototype doors showed a performance that was a significant improvement over the baseline material. This finding was well received by the project team members.

6.3 Deliverables/Products Developed

- Prototype door for 2002 Jeep.

6.4 Technology Transfer Activities

6.4.1 Proprietary Reporting

- Presented at 2004 closeout meeting.

6.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

7. Lightweight Front-End Structure (ASP110)

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- Quantech Global Services
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- Stelco Inc. Hilton Works
- U.S. Steel
- Dofasco
- Auto/Steel Partnership

Project Duration: February 2003 – January 2006

7.1 Executive Summary

Light-weighting initiatives have demonstrated that advanced high-strength steels (AHSS) can be effectively utilized for mass reduction strategies, providing required performance and lower overall cost. Constraints in implementing AHSS scenarios are joining and forming and high-volume manufacture and assembly.

The Lightweight Front-End Structure project was a purely analytical, parametric study of automotive front-end design sensitivities, sponsored and overseen by the Auto/Steel Partnership (A/SP).

The project, utilizing math data from the original Ultra Light Steel Auto Body (ULSAB) initiative, was organized into a series of independent, and selectively discrete activities, which together formed the basis of an integrated strategy for further development of a lightweight front-end structure utilizing AHSS. The various methodologies employed, included: design of experiments, response surface modeling (RSM) and computer-aided optimization (CAO).

A methodology to optimize mass and cost of a structure, subject to performance and manufacturing criteria was developed in Phase I of the Lightweight Front-End Structure project. This methodology was employed effectively in Phase II of the Lightweight Front-End Structure Project.

7.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Due to funding and timing constraints, the study was divided into two phases. The first phase focused on the determination of the allowable design space, and benchmarking and target setting for structure performance. Also included in this phase were, initial bumper characteristics development and web site development.

The objectives of the Lightweight Front-End Structure project were to develop a methodology, a knowledge database and an associated user interface that would provide access to mass and cost information, for variations of a given front-end package. Two front-end packages were considered in this study – the initial front-end package and the upgraded front-end package. The structure had to meet stringent stiffness, modal and crash performance criteria, and had to be manufacturing feasible. Access to the database should allow early trade-off decisions to be made that comprehend effects of more front-end content and less space, on mass, cost and performance. This project focused on the utilization of AHSS to mitigate cost and mass.

Optimization of the baseline **i**nitial front-end package resulted in a double five star NHTSA rating and an overall good IIHS rating. This was achieved with a mass savings of 12 kg and a cost reduction of $69, compared to the baseline initial package. Furthermore, the baseline initial front-end package did not meet all the target requirements. The optimized initial package also has a bumper design that is very efficient in high-speed impacts.

Optimization of the baseline upgraded front-end package resulted in a double five-star NHTSA rating and an overall good acceptable IIHS rating. This was achieved with an addition of 16 kg of mass and a cost increase of $15, compared to the baseline upgraded package. The increase in mass is required as the baseline upgraded package did not meet the target requirements.

The upgraded front-end package was obtained from the initial front-end package by replacing the 3.1 litre V6 engine/powertrain package by a larger 3.6 litre V6 engine/powertrain package. Furthermore, the 196/60 R15 wheel/tire was replaced by a larger 205/60 R16 wheel/tire. The upgraded front-end package has a 50mm shorter front-end and represents a 180 kg heavier vehicle. In addition, the upper and lower rails were modified in order to accommodate the bigger engine and wheel. This resulted in a rail architecture that had a significant departure from the straight rails of the initial front package. The upgraded front-end package also has a bumper design that is very efficient in high-speed impacts.

The second phase determined, for each parametric variation, the cost, mass and performance effects, in order to arrive at an optimized design that would meet the targets established in the first phase. The findings were compiled into a comprehensive database and an intuitive web tool (Proteus) was developed providing access to the data in the database.

The objective of the Phase II of the Lightweight Front-End Structure project was to accelerate the introduction of the higher grades of AHSS (DP800 and above) into vehicles, at little or no cost, and consequently accelerate efforts in vehicular lightweighting. The project focused on benchmarking, developing and documenting proven solutions that balanced the interaction of material, manufacturing and performance. The study focused on the automotive front-end system solutions that address high-volume manufacturing and assembly. The AHSS solutions developed in Phase II will provide choices and consequences that address real-world challenges faced in the vehicle development process.

Front rail assembly (DP800) and front bumper assembly (DP980) were designed, manufactured and assembled into a donor vehicle. The AHSS design was validated by conducting an NCAP 35 mph rigid barrier crash test. The AHSS design (Figure 7-1) achieved a mass reduction of 8.77 kg (22.36%) compared to the baseline design (Figure 7-2). The NCAP performance of the AHSS design (20) was superior to that of the baseline design (6). The IIHS, static and dynamic stiffness performances were similar to those of the baseline design. The AHSS design has the following features:

- Octagonal 3-piece tailor-welded rail inner and outer pieces with symmetric flanges and tapered front section.
- Two-piece rail tailor-welded extension design with a reinforcement.
- Rail inner reinforcement.
- Symmetric LH/RH rail assemblies.
- Two-piece double box bumper design with energy absorbing features.

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. The AHSS design was validated by conducting an NCAP 35 mph rigid barrier impact test on the donor vehicle fitted with the AHSS rails and bumper.

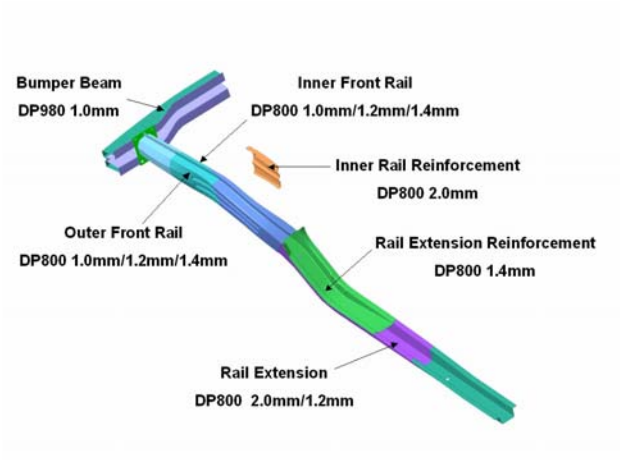

Figure 7-1. AHSS LH Rail Assembly

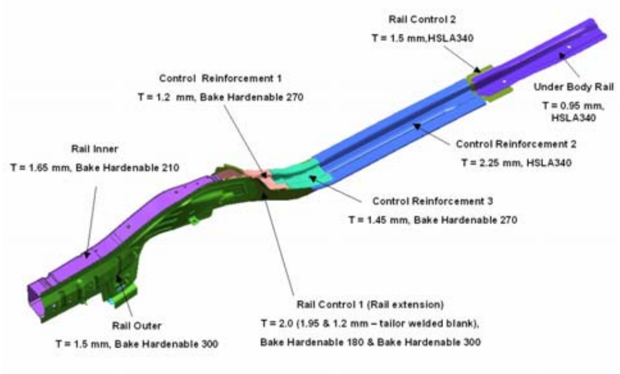

Figure 7-2. Baseline LH Rail Assembly

It can be concluded that the use of AHSS in conjunction with effective part design can result in significant mass reductions in crash applications. 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 due attention is given to manufacturing constraints early in the design process.

7.2.1 Computer Modeling Work

A knowledge-based engineering tool was developed in order to comprehensively archive and provide easy access to the "lessons learned" from the suite of investigations undertaken. This tool, named Proteus, provides access to all the data that was generated from the analyses and experiments during this project, in an easy and intuitive fashion. Proteus will help in determining the effects of various parameters and constraints on significant responses and provide cost and mass for a given vehicle performance. Proteus is scalable/extensible; it has the ability to accumulate information from new investigations.

7.3 Deliverables/Products Developed

- Methodology.
- User Interface.
- Proteus (knowledge-based engineering tool).

7.4 Technology Transfer Activities

7.4.1 Proprietary Reporting

- Final technical report to A/SP.
- Milestone Reports.

7.4.2 Non-Proprietary Publications and Proceedings

[1] Manufacturing Feasibility Report, Stamping Group.

[2] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org

8. Sheet Steel Fatigue (ASP160)

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- National Steel
- Bethlehem Steel
- Rouge Steel Company
- Dofasco, Inc.

Project Duration: January 2001 – October 2010

8.1 Executive Summary

The Sheet Steel Fatigue Characteristics project was undertaken to develop data that would facilitate the structural analysis phase in optimizing automotive body design. As designers attempt to optimize steel bodies in the design phase, minimizing metal thicknesses and exploring steel grades with higher strength, they need additional design data to support their work. One property that is becoming progressively more critical is fatigue. Fatigue properties data will enable more accurate prediction of the performance of components that are subjected to cyclic loads in the design analysis phase. In order to derive the most useful data for the effort expended, material grades were judiciously selected and procedures, such as test sample preparation, were rigidly defined. A significant amount of data was generated, and additional work was planned to compile and verify the data and identify and prioritize subsequent phases of work in frame and body construction methodologies.

In the era when vehicle mass was not a drawback, and in fact was often perceived as an advantage, the primary concern in the structural design of vehicle bodies was rigidity. When it became necessary to reduce body mass in order to comply with mandated corporate average fuel economy (CAFE) requirements, structural design engineers began to re-examine body designs to identify areas where mass could be reduced without compromising rigidity and load carrying requirements. One promising way to accomplish both is to reduce metal thicknesses and utilize higher-strength steels. As structural components were optimized and thinner gauge, higher-strength materials considered, predicted stress levels rose and component fatigue life became a consideration. In order to assess the fatigue performance of a material in the design phase, it became necessary to know the fatigue characteristics of the materials being considered.

8.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objectives of this project are to:

- Investigate the fatigue characteristics of sheet steels, particularly those with higher strengths that will be instrumental in reducing or containing vehicle weight.
- Investigate the fatigue characteristics of joints such as resistance spot welds, gas metal arc welds and laser welds.
- Develop sound durability assessment criteria to assess optimized lightweight vehicle structures.

Status:

- Testing and analysis has been completed on the fatigue characteristics of AHSS joined by resistant spot weld. A detailed variability study has also been completed.

- Fatigue testing has been completed on gas metal arc welds (GMAWs) used to join fourteen combinations of DP600 and DP800 components.
- A two-phased fatigue test program of GMAW and laser-welded specimens is underway. This test program will also investigate the effects of weld geometry variation. Phase IA has been completed. Phase IB is in progress.
- A simplified durability assessment procedure has been developed. A detailed report on the new procedure has been provided to the A/SP Future Generation Passenger Compartment (FGPC) project team.
- The team completed Phase IB GMAW and laser-weld fatigue testing and prepared and submitted the final report on the Phase IB project. The report included an analysis of the effects of weld geometry variation.

8.3 Deliverables/Products Developed

- Phase IA an IB Reports.
- Fatigue Test Database describing the fatigue characteristics of sheet steels.
- Fatigue Test Database describing the fatigue characteristics of resistance spot welds, GMAWs and laser welds.
- Sound durability assessment criteria to assess optimized lightweight vehicle structures.

8.4 Technology Transfer Activities

8.4.1 Proprietary Reporting

- Annual Auto/Steel Partnership Technical Communications Meeting, Auburn Hills, MI, February 22, 2001.

8.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

[2] Four SAE papers, including two in April 2009:

  – "Durability of Advanced High-Strength Steel Gas Metal Arc Welds."
  – "Influence of Weld Process Parameters on the Geometric Variability of GMAWs."

[3] Two SAE papers accepted for 2011 World Congress on: "MIG Weld Variation" and "Analytical Approaches."

9. Strain Rate Characterization (ASP190)

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- Ispat Inland, Inc.
- University of Dayton Research Institute
- Oak Ridge National Laboratory (ORNL)

Project Duration: January 2001 – 2009

9.1 Executive Summary

Crashworthiness characterization of advanced high-strength steels (AHSS) requires testing of materials and structures under increased strain rates, large plastic strains, and large displacements that are characteristic of actual impact events. The AHSS characterization involves testing at several different length scales. The intrinsic material properties are investigated using the coupon-level specimens where the material is exposed to simple stress states that can be reduced to the equivalent stress and strain measures used in formulation of constitutive models. The coupon tests involve uniaxial tension and compression in plane-stress conditions. High-speed hydraulic equipment is used to impose constant velocity in order to determine material response to different loading rates. At a higher length scale, the characteristic plastic hinge mechanism responsible for crash energy absorption in AHSS structures is investigated using the double-plate test. This test has shown that the strain-rate sensitivity of AHSS in bending under out-of-plane compression exhibit trends that cannot be fully explained using the plate bending models derived from material behavior under uniaxial plane stress. At the component level, AHSS properties in tubular structures are investigated using specialized hydraulic equipment that allows constant crush speeds up to 8 m/s. In automotive design, the structural integrity of AHSS components is primarily provided by spot welds. The response of spot welds under different loading velocities and loading states have also been characterized in this project.

The above experiments provide high-quality data for development of material and structural FEM models for AHSS and, thereby, enable more accurate modeling and design of light-weight, crashworthy vehicles. The developed experiment technology is also directly relevant to other automotive materials as it provides a systematic approach to characterization and comparison of crashworthiness of new automotive materials.

It is important to determine the behavior of advanced high-strength steels (AHSS) under impact conditions in order to use the correct material properties in crash simulations. As previously reported, the material responses of specific AHSS were investigated to provide material data for FEM analysis. Tensile tests on DP600 and DP780 dual-phase steels were conducted for as-received and baked samples to examine the effect of baking on the static and dynamic material response. In the latest reporting period, these material responses were digested into representative curves and data sets were generated suitable for input into crash simulations.

Additional crush tests were performed on DP780 tubes in the as-received and bake hardened conditions. An analysis method was

developed to accommodate crush test data from facilities and test fixture designs.

9.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Objectives:

- Develop new experimental methods for characterization of crashworthiness and strain-rate sensitivity of both AHSS 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.
- Initiate new, robust spot-weld finite-element formulation procedures for modeling various modes of spot-weld failure as a function of impact, welding conditions and materials while maintaining the current computational efficiency.
- Establish an experimental database on the performance of resistance spot weld in AHSS components during impact.
- Determine the effect of paint baking on the static and dynamic material response of selected AHSS.
- Develop representative material data sets for selected AHSS, which can be used in CAE modeling.

Accomplishments:

- Developed procedure for new crashworthiness characterization test based on parallel-plates buckling.
- Developed and conducted constant velocity crash experiments on circular tubes.
- Developed hydraulic tests for strain rate characterization of high-strength steels (HSS).
- Develop www database for display and analysis of coupon, spot-weld, and tube crush experiments.
  - Developed test method for investigation of strain-rate effects of spot welds.
  - Determined the effects of bake-hardening on the static and dynamic tensile behavior of DP600 and DP780 dual- phase steels.
  - Results from tensile tests (DP600 and DP780) were used to create representative material response data sets suitable for input into impact modeling programs.
  - Generated high rate tube crush data for as received and baked tubes (DP780).
- A new method for characterization of strain rate sensitivity under automotive strain rates has been developed. This method uses multiple measurements of material response in a single testing apparatus. It enables the correlation of the measurements and identification of test areas for further improvement. The new specimen configurations for plate materials are under development.

Tensile tests performed on DP600 and DP780 dual-phase steels established the effects of pre-straining, bake hardening, and increasing test rate. The results from the tensile tests were used to generate representative curves of the material response. The tabulated data from the curves can be used as input for finite element analyses of DP600 and DP780.

Crush tests were performed on DP780 tubes in the as-received and baked conditions at multiple strain rates. An analytical methodology was developed to enable analysis of crush data from dissimilar test setups. Trends showed a 3% increase with bake hardening in the average crush load and energy absorbed across a test rate of 0.254mm/s to 7250mm/s.

9.3 Deliverables/Products Developed

- Data sets on AHSS strain rate sensitivity.

9.4 Technology Transfer Activities

9.4.1 Proprietary Reporting

- Talks at A/SP Offsites and USAMP Offsite.
- Great Designs in Steel presentations.

9.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org

[2] Presented two technical papers to SAE2009 World Congress: Dynamic Spot Weld Testing & Bake Hardening Effect of Dual Phase Steels.

10. Tailor-Welded Blank Applications and Manufacturing (ASP210)

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- Dofasco, Inc.
- Faunhofer USA
- ATB
- AWS
- MakAuto
- Medina Shiloh Noble Industries
- Olympic Laser Processing
- Procoil Laser
- Renault Automation
- Sondronic
- Tailor Steel
- Thyssen Krupp
- TWB
- VIL
- Rouge Steel

Project Duration: June 2001 – December 2003

10.1 Executive Summary

The tailor-welded blank (TWB) industry continues to experience steady growth. Each auto company now has TWB applications and the growth rate is approximately 25-30% per year in North America, Europe and Japan. The leading objectives continue to be cost reduction, structural improvement and mass reduction. Certain companies continue to recognize quality improvements as a major objective, especially with door inners and one-piece body side TWBs. While there continue to be numerous small (under 0.75 meters), simple, one-weld applications, the growth is spreading into larger, more complex products. Japanese and European aperture designs tend to be markedly different than those seen in North America. The North American apertures tend to be a body side with multiple, long welds that are costly to process and weld. European and Japanese designs tend to be body side inner panels with two to three short welds on shallow draw panels that are simpler to process. The shallow draw panels are also more conducive to integrating high-strength steel into the body side.

The main objectives of the project were to:

- Investigate the manufacturability and formability of high-strength steel (HSS) and advanced high-strength steel (AHSS) tailor-welded blanks.
- Demonstrate that these products can be used to produce automotive components of significantly lower mass. The application of high-strength low-alloy (HSLA) steels and AHSS offer the potential for further weight reduction. However, uncertainty exists regarding the weld processes for these products and the resultant ductility of the weld and heat-affected zone. Develop manufacturing techniques and validate to assure reliable,

high-volume HSS and AHSS tailor-welded blanks.

10.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Following were the achievements:

- Fatigue tested laser welds in AHSS tailor-welded blanks DP600-MPa and DP800-MPa material tests have been completed.
- Defined some product design and manufacturing process modifications for control of springback and side-wall curl on tailor-welded blank stampings of different strengths.
- Evaluated benefits of hybrid laser/arc welding processes for AHSS tailor-welded blanks.

The charter of this state-of-the-art study was to identify current and projected developments in TWB applications and manufacturing technologies. The TWB designation is used in the broad sense to include conventional TWBs, two or more sheets of steel welded along adjacent edges as flat blanks prior to forming, TWTs of multi-gauge or grade side-walls, and patch-type TWBs, or a steel "patch" overlapping another steel blank. Although the conventional joining method has been either CO_2 and YAG laser or resistance mash welding, other joining methods were also considered, including spot welding in the case of patch-type TWBs. Applications and technologies of interest in the study include current and near-future possibilities.

The majority of weld systems and applications investigated are in production today. All systems are evolving as welding experience is gained and product applications evolve in complexity. The dominant welding technology was confirmed to be shifting more toward laser from resistance mash seam, with a significant focus on YAG laser because of its overall operating robustness and flexibility for non-linear requirements. Applications are also becoming more complex with longer weld lines, as on door inner and body side aperture panels, steels that are more difficult to weld, and NLW seams. A significant aspect of this study included exploring the application interests and state of technology development in these areas throughout North America, Europe, and Southeast Asia, primarily Japan.

One objective of this investigation was to evaluate the direction of TWB applications and welding technologies to help guide research initiatives. The TWB industry has evolved rapidly over the past 10 years with major developments in:

- Broad expansion of the supply base.
- High-power welding sources.
- Varied edge preparation techniques for butt welding.
- Flexible welding systems utilizing beam switching, flexible jigs, etc.

In spite of the industry's steady growth with "easier-to-justify" applications, the North American automotive and steel companies recognize that long-term continued growth would require improved product and process optimization. TWB supply costs are a major barrier to implementation because of welding costs and the logistical costs of inventory, material handling, shipping, etc. Weld cost can be reduced through improved edge preparation technologies, increased weld system throughput, or increased welding speeds and processing efficiencies, and by better product design in light of the varied processing requirements seen across the supply base. In practice, different companies have taken a variety of approaches to reduce logistical costs. The Japanese have integrated significant portions of their TWB welding supply with their in-house blanking and stamping operations to reduce inventories, material handling and damage while improving communication. Several European companies have developed standard practices for packaging and pallet design to reduce material handling costs and damage. In North America, a number of companies are developing technologies that can develop precise edge fit-up and perform NLW. NLW allows for refinements in material utilization, mass reduction and forming complexity in many applications.

Another purpose of this study was to learn about TWB application design and welding technologies to help further advance the North American TWB supply industry. The principal sources of information for this study were public literature references, individual interviews, site visits and company-supplied documentation. Information or developments that companies did not want to publicly disclose were not pursued for inclusion with this study.

10.3 Deliverables/Products Developed

- None at this time.

10.4 Technology Transfer Activities

10.4.1 Proprietary Reporting

- None at this time.

10.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

11. Tribology (ASP230)

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- United States Steel Corporation
- Stelco, Inc.
- TribSys, Inc.

Project Duration: October 2008 – Present

11.1 Executive Summary

Lubricants have historically been used in the forming of sheet metal stampings to reduce friction, improve formability and minimize die wear. Lubricants likewise provide corrosion protection. The anticipated increase in the use of advanced high-strength steels (AHSS) places a greater emphasis on understanding the process parameters associated with die wear, such as heat build-up and die scoring, and dimensional stability caused by springback variation. The contribution of interfacial friction to springback variation is not known. AHSS grades may require different lubricant and/or die materials to minimize the friction and die wear.

The objective of the project is to conduct stamping simulation tests to study the effects of tribology, the interrelationship of lubrication, friction and wear, on the stamping performance of AHSS. Stamping performance in this project is defined as minimizing die wear and maximizing dimensional stability. The understanding of the contribution of lubricants to errors in springback prediction when using finite element analysis will also improve dimensional performance.

11.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The ability to fully realize the benefits of AHSS depends upon the ability to aggressively form these steels into challenging parts. These steels have been shown to cause die failures in early implementations. This project is intended to improve the tribological understanding of the interaction among AHSS, tooling, coatings, and the forming process so that the proper system can be selected to successfully manufacture stamped automotive parts. The project objectives were to:

- Identify the tribological factors that contribute to successful stamping of AHSS. This includes the achievement of consistent, moderate coefficient of friction, minimized tool wear, and minimized galling/die pick-up.
- Identify the most effective pierce clearance (burr height) when piercing AHSS.
- Determine die material and coating performance for AHSS.

The project was divided into two phases:

In Phase I, a progressive die was built in 2008 that could test 17 piercing operations, 12 flanging, 15 trimming, and six forming conditions with each of 100,000 hits. Six coatings from three vendors were evaluated for durability.

- Of the 100,000 target hits, 60,000+ hits are completed.
- Design changes and extra material were needed to complete Phase I. Design changes include ball-bearing guide pins and directional heels for robustness of the die and ease of testing. New test materials were added to complete the current AHSS supply.
- Phase I was completed in March 2009.
- Project was presented at 2009 Great Designs in Steel Conference.

Phase II includes the following tasks to continue testing coatings and analyze correlations to the A/SP die:

- Test force Phase I successes-to-failure.
- Add IRMCO lubrication.
- Make all pierce one clearance – burr height or clearance
- Keep the high-performing materials constant while varying coating.
- Keep the high-performing coatings constant while varying material.
- Test DP780 and DP980 for differences in tool wear.
- Change conditions (different trim angle, etc.); adjust detail attachment for easier shimming.
- Re-test some trim steels with lower hardness.
- Record and test surface finish.
- Test new coatings.

11.3 Deliverables/Products Developed

- Fully documented coating fatigue test procedure.

11.4 Technology Transfer Activities

11.4.1 Proprietary Reporting

- Presentation given at Great Designs in Steel, 2009.
- DOE Annual Report completed.

11.4.2 Non-Proprietary Publications and Proceedings

[1] Paper to be presented at 2011 SAE Congress.

[2] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

12. Future Generation Passenger Compartment (ASP240)

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- DTA
- University of Michigan
- U.S. Steel Corporation

Project Duration: March 2005 – January 2007

12.1 Executive Summary

Various studies conducted by the automotive Original Equipment Manufacturers (OEMs), American Iron & Steel Institute (AISI), International Iron & Steel Institute (IISI) and Auto/Steel Partnership (A/SP) have clearly demonstrated that advanced high-strength steel (AHSS) 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 functionality 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 multi-disciplinary systems that can use the current and future AHSS in combination with an innovative optimized design.

The USAMP and A/SP strategy for the Future Generation Passenger Compartment (FGPC) project is to propose a new passenger compartment and underbody that can provide the OEMs with an example of AHSS usage in combination with a highly-optimized design.

12.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The strategy for Phase I of the FGPC project was to develop a robust design that considered two differing perspectives, near-term or five-year and long-term or 15-year. Near-term is defined as the knowledge gained from FGPC Phase I used in combination with technology that could be applied to a present vehicle with minor modification. Issues relating to manufacturing, joining and material selection are considered within reach. FGPC Phase II applied the knowledge gained in Phase I to a donor vehicle selected jointly by USAMP and A/SP.

Near-term material 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. However implementation was addressed in the FGPC Phase II, the validation phase.

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. For example, though currently unavailable, the optimization indicated that there would be an opportunity to use a 1550 MPa grade steel as a Class A surface. There are many approaches that may achieve this outcome such as an exposed hot stamp boron.

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 body-in-white as a baseline model, the FGPC objective was to modify the body-in-white to accommodate both diesel and fuel cell powertrains and to reduce the body-in-white mass while still meeting the requirements of the new IIHS Side Impact and Roof Crush regulations.

The goal of the Phase II project was to continue to develop a mass efficient roof structure on the B-pillar less, light truck structure that was the used in Phase I.

These goals included:

- Providing a mass efficient design of the roof structure by further optimizing the Phase I Composite Insert Nylon Steel Design through use of analytical multi-objective optimization.
- Developing designs that continue to meet the enhanced FMVSS 216 Roof Strength requirements as proposed by the MEARS team.
- Investigation of alternate steel only design concepts that would meet the requirements in a mass efficient manner.
- Investigation of continuous bonding methods including laser welding and weld bonding to gain further mass efficiencies.
- Providing a final design concept that is manufacturing feasible by conducting metal forming simulations and process evaluations on parts that are new or use ultra high-strength steels like boron steel or dual-phase steels.
- Developing a cost model and perform a detailed cost analysis of the final design concept accounting for the manufacturing process and assembly changes in the design.
- Presenting a final design concept that represents an Optimal Design Concept-of-Mass Efficient Architecture for Roof Strength Performance.

The optimization methods applied to the FGPC project achieved an 11% mass reduction of the modified parts of the body-in-white and door impact beams, and 30% mass savings over a conventional in-class vehicle's body-in-white and IP beam, the final concept design shows a 31% mass reduction.

Based upon these results it is possible to conclude that if the FGPC design methodology is applied to a similar size vehicle a 30% mass reduction is feasible. Furthermore, the resulting design has been shown to be a robust solution that is insensitive to increases in the curb weight. Task 7.5 proved that under the IIHS Side Impact and Roof Crush loadcases, a 350 kg increase in curb weight comfortably met the requirements of the test.

The Phase I final design concept model was validated in terms of the overall load carrying capability at the beginning of the Phase II study. With the use of AHSS throughout the greenhouse, and the introduction of Composite nylon inserts in key areas, the Phase I final concept model was able to carry a normalized load of 3.06. Through design optimization, the mass of the steel components in the roof structure reduced by 5.2 kg. The overall mass of the roof structure including the nylon inserts was 1.3 kg higher than the donor model. More significantly, this Phase I final concept model allowed the roof structure to hold a 40% higher normalized load.

The Phase II Final Design Concept Model had a mass savings of 5.7 kg when compared to the Phase I Final Concept Model and 4.4 kg compared to the Donor Model. In order to achieve the mass savings, a combination of design changes, advanced and ultra high-steel materials, additional spot welds and composite nylon inserts were included in the design. The study determined that the C-Pillar stiffness contributed the most to the overall roof structure strength. Composite nylon inserts and boron steel, coupled with design changes were used to help strengthen this area, allowing gauge reductions and material substitutions to occur throughout the greenhouse structure to achieve the final mass savings.

12.3 Deliverables/Products Developed

- 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.
- Mass efficient roof structure.

12.4 Technology Transfer Activities

12.4.1 Proprietary Reporting

- Talks at A/SP Offsites, USAMP Offsites and at Great Designs in Steel.

12.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

13. Future Generation Passenger Compartment Validation (ASP241)

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Project Duration: October 2006 – Present

13.1 Executive Summary

The objective of the Future Generation Passenger Compartment (FGPC) Validation project is to validate the findings of the ASP240 project on a five-passenger, four-door sedan production donor vehicle. This project aims to reduce passenger compartment mass by 25% or greater with cost parity relative to 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 2.5 times the vehicle weight roof strength test. Further, it will maintain performance in static and dynamic stiffness, durability and front and rear crash requirements.

13.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project is separated into four phases:

Phase I – Concept development—ASP240 completed.

Phase II-a – Validation on a production donor vehicle—A current production donor vehicle was selected and work was initiated in February 2007. All project design tasks are complete.

Phase II-b – Development of advanced steels—A joint effort amongst the National Science Foundation (NSF), the Department of Energy (DOE), the American Iron and Steel Institute (AISI) and the Auto/Steel Partnership (A/SP) has resulted in funding for eight university proposals on fundamental steel research to support the development of the desired steels. Work is being conducted under project ASP280.

Phase II-c – Concept development of large truck cab comprehending 2.5 times the roof strength criteria—Mass Efficient Architecture for Roof Strength (MEAR) ASP270. Passenger compartment concept for large vehicles (trucks and SUVs) where structure is controlled by 2.5 times the roof strength criteria – Donor vehicle design has been selected and work initiated on the development of a mass efficient concept. Baseline performance and performance targets have been established. Three concept designs are currently in the development stage.

Phase II-d – Comprehend opportunities and influence of mass-compounding—Quantification of mass-compounding – This project has been initiated to develop a mass-compounding model developed with a database of current production vehicles. This Phase identified secondary mass savings as high as 1.5 times primary mass savings based on data from 33 vehicles. The next portion of this phase will increase the database to include an additional 100 plus vehicles complete 09Q1.

Phases III and IV are original equipment manufacturer (OEM) internal.

- Phase III – Roll-out learnings into advanced vehicle development
- Phase IV – Production design.

13.3 Deliverables/Products Developed

- Validation of FGPC Guidelines and concept designs on a production donor vehicle.
- Concept design of large truck cab.
- Mass-compounding model with database of current production vehicles.

13.4 Technology Transfer Activities

13.4.1 Proprietary Reporting

- Talks at A/SP and USAMP Offsites and Great Designs in Steel.

13.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

14. NSF Funding for the Development of a 3rd Generation Advanced High-Strength Steel (AHSS) (ASP280)

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Project Duration: July 2007 – March 2009

14.1 Executive Summary

This three-way USAMP Auto-Steel Partnership collaboration with the NSF and DOE was established to conduct the fundamental research required to develop a 3rd Generation Advanced High-Strength Steel (AHSS) that is higher in strength and more formable than currently available commercial grades of AHSS with the potential of being more cost effective than stainless steels and TWIP steels. One of the tasks of the ASP240 Future Generation Passenger Compartment project was to perform structural optimization with unrestricted strength limitations to define the upper strength bound for auto body steel for optimized mass reduction. Several areas of the auto body were identified that would benefit from higher strength materials applications. An additional 5-8% mass reduction is possible in those areas of the vehicle. One of the tasks of the ASP240 Future Generation Passenger Compartment project was to perform structural optimization with unrestricted strength limitations to define the upper strength bound for auto body steel for optimized mass reduction. To pursue these research objectives further, the NSF solicited proposals and competitively awarded eight university investigators. The ASP and DOE provided oversight and monitored technical progress.

14.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objective of this project was to provide a portion of the funding (25%) for the fundamental research required to develop a cost effective family of 3rd Generation AHSS that could ultimately be applied for mass reduction in the auto body. Additional funding was provided directly by DOE (25%) and NSF (50%). The research was done utilizing the processes of the NSF. If successful, the research would provide the basis for the commercial development of cost effective 3rd Generation AHSS by the A/SP steel members, as shown in Figure 14-1.

An industry based steering committee was formed with members from A/SP member companies. They included representatives from steel research centers, mills and automotive applications centers and advanced materials representatives from the automotive companies. The steering committee helped coordinate additional support for the NSF researchers and became the technology transfer interface for the research back into industry.

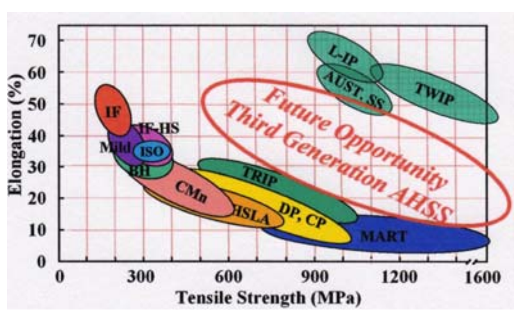

Figure 14-1. Opportunity for Development of 3rd Generation AHSS Grades

Table 14-1 lists the accomplishments of the projects during the period ended March 31, 2009.

14.3 Deliverables/Products Developed

- Website established for storing and sharing of information amongst investigators.
- Proceedings of Annual Reviews held among Principal Investigators on April 10, 2008 and May 14, 2009.
- DOE Roadmap under development.

14.4 Technology Transfer Activities

14.4.1 Proprietary Reporting

- Initial meeting of researchers held April 10, 2008, and posting of presentations.
- Visits to universities by ASP-NSF-DOE representatives.
- Proceedings and web postings from second research review with principal investigators held on May 14, 2009.

14.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

Table 14-1. Summary of NSF Awardees and Progress Through 3/31/2009

University	Professor	Topic	Progress Summary
Carnegie Mellon University	Warren Garrison	AHSS through microstructure and mechanical properties	Void nucleation/growth studied to assess effects of multi-phase microstructures on steel properties.
Case Western Reserve U.	Gary Michal	AHSS through C partitioning	Carbon partitioning and austenite stabilization studied via double stabilization thermal process.
Catholic University of America	Abu Al-Rub Rashid	AHSS through particle size and interface effects	Particle size and interface effects studied.
Colorado School of Mines, Ohio State University	David Matlock (CSM) and Robert Wagoner (OSU)	Collaborative GOALI Project Formability and Springback of AHSS	Austenite stability/ Quenching and Partitioning in AHSS microstructures with high retained austenite; two alloy systems selected and being studied.
Drexel University	Surya Kalidindi	FEM using crystal plasticity simulation modeling tools	Project Suspended and work stopped
Ohio State University	Ju Li	Multi-scale modeling of deformation for design of AHSS	Extended time-scale simulation of coupled diffusive-displacive processes.
University of Missouri-Rolla	David C. Van Aken	AHSS through nano-acicular duplex microstructures	Explored duplex ferrite and austenite for higher strength.
Wayne State University	Susil K. Putatunda	High strength high toughness bainitic steel	Explored use of austempering for fine structure and high ductility and toughness.

15. Strategic Roadmap for Joining Next Generation Lightweight Applications of Steels (ASP310)

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- General Motors Corporation
- Chrysler Corporation
- Auto/Steel Partnership
- ArcelorMittal
- Nucor Steel
- U.S. Steel
- LASAP Corp.
- Dofasco, Inc.

Project Duration: June 2008 – Present

15.1 Executive Summary

Recently developed advanced high-strength steels (AHSS) have the potential for significant mass savings in automotive applications due to the material down-gauging made possible by the AHSS strength and toughness. Currently however, the full benefit cannot be achieved because of technical limitations encountered when joining together components made from AHSS. The automotive industry lacks a roadmap for joining new lightweight steels beyond traditional methods. This project was initiated to perform a gap analysis in joining technologies.

Universities, laboratories and other organizations are working with new approaches to joining steels. These new technologies need to be evaluated and, if promising for automotive applications, developed into production-capable processes. This project proposes to identify, evaluate and, if appropriate, plan for the development of these new technologies.

In the short term, this effort will provide knowledge in joining constantly evolving steels and will prioritize an Auto/Steel Partnership (A/SP) lightweight development portfolio to meet these joining needs. In the long term, it will focus the year over year research investment needed to deliver appropriate joining technologies, which will ultimately improve the lightweight applications and competitiveness of steel.

15.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

This project has created a Steel Joining Strategic Roadmap identifying needed research to close joining technology gaps. This Roadmap is being utilized by A/SP to identify future steel joining technical development projects (project portfolio).

The project goals are to:

- Identify potential new joining technologies.
- Prioritize these new technologies by risk/benefit assessment.
- Create a roadmap (a list of projects identifying technologies and infrastructure requiring solutions) to develop processes to join AHSS in high-volume automotive manufacturing environments.

A Statement of Project Objectives (SOPO) has been written to define the ingredients and tasks to accomplish and deliver the roadmap. An industry expert, LASAP was contracted through the A/SP to lead this effort. This individual then solicited other experts to pool information from global industry and worldwide research forums specific to the unique joining technologies for these lightweight applications.

The information gathering involved several modes to identify gaps:

- Written survey
- Face-to-face interviews with original equipment manufacturers, steel suppliers, and joining suppliers, R&D institutes, national labs and universities
- Literature search
- Patent reviews.

15.3 Deliverables/Products Developed

- A Roadmap and Prioritized Project Portfolio that will be used to initiate new lightweight joining projects at A/SP. Total of 16 potential projects were identified (8 high priority) as follows:
  - 10 welding projects
  - 2 adhesive projects
  - 2 mechanical joining projects
  - 1 modeling project
  - 1 NDT project.

15.4 Technology Transfer Activities

15.4.1 Proprietary Reporting

- DOE Semi-Annual and Offsites.
- Report from LASAP for USAMP.

15.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

16. Vehicle Structural System Benchmarking (ASP330)

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- General Motors Corporation
- Chrysler Corporation
- U.S. Steel

Project Duration: January 2009 – Present

16.1 Executive Summary

The project will data mine 100+ vehicles available in the A2MAC1 vehicle teardown database in order to identify normalized comparison approaches and comprehend relative mass performance between material, manufacturing technology and system architectures. The project will also investigate closures, body-in-white, suspensions, IP beams, bumpers, seats, wheels and sub-frames.

A key goal is to develop a predictive model for expected sub-system mass.

16.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The project will benchmark vehicle systems (closures, suspensions, body-in-white, etc.) on current production vehicles to establish a reference mass baseline. The data will then be used to compare material, manufacturing technology and architectures to establish relative mass performance and identify best-in-class mass performance across 15 vehicle sub-systems.

- Identify current mass performance of vehicle structural system and establish a reference mass baseline.
- Identify relative mass between design strategies (material, manufacturing technology and architectures).
- Identify best-in-class mass performance of vehicle structural systems (closures, suspensions, body-in-white, etc.) and determine material, manufacturing, and architectural strategies and associated structural, cost and $C0_2$ lifecycle assessment performance.
- Set data derived mass targets for future lightweighting projects.

16.3 Deliverables/Products Developed

- A vehicle mass database with statistical models for predicting mass of sub-system for benchmarking.

16.4 Technology Transfer Activities

16.4.1 Proprietary Reporting

- DOE Semi-Annual Report and Offsite.
- Presentations at Great Designs in Steel.

16.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

17. Lightweight Front Suspension Lower Control Arm (ASP340)

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- U.S. Steel
- Nucor Corporation
- ArcelorMittal
- Severstal N.A.
- Republic Engineered Products
- Timken
- Multimatic
- AISI

Project Duration: May 2009 – March 2010

17.1 Executive Summary

The objective of this project was to develop lightweight sheet and forged steel proof-of-concept front lower control arm (FLCA) designs that achieve equivalent structural performance and function at a reduced cost relative to the baseline forged aluminum FLCA assembly. A current production original equipment manufacturer (OEM) FLCA assembly was used to establish the baseline for package, performance, mass, and cost.

Computer-aided engineering structural optimization methods were used to determine the initial candidate sheet steel and forged designs. Two sheet steel FLCA designs and one forged steel FLCA design were selected and developed to meet all typical performance criteria.

An iterative optimization strategy was used to minimize the mass of each design while meeting the specified stiffness, durability, extreme load, and longitudinal buckling strength requirements. In order to achieve sufficient mass reduction with the forged design, an aggressive 3mm minimum gauge manufacturing target was assumed.

The manufacturing cost was estimated for the sheet steel designs relative to the baseline design for three production volumes. The costs of the forged design could not be assessed due to insufficient data.

The results of the study indicate that a clamshell design based on DP780 steel sheet achieves equal mass to the baseline assembly, and up to a 34% reduction in manufacturing cost. The I-beam design based on DP780 and DP980 sheet, DP780 tube, and HSLA550 was predicted to have a 2% (0.05 kg) mass increase relative to the baseline assembly, and up to a 21% reduction in manufacturing cost. The forged design based on AISI 15V24 grade material and the 3mm minimum gauge target was predicted to have a 4% (0.13 kg) mass increase relative to the baseline assembly.

All sheet steel designs were deemed manufacturable based on forming simulations, and relevant production application examples. Manufacturing studies are recommended to assess the ability to meet the assumed aggressive minimum forging gauge target and to provide a basis for developing the associated manufacturing costs.

17.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The objective of this project was to develop lightweight sheet and forged steel FLCA proof-of-concept designs that achieve equivalent structural performance and function at a reduced cost relative to the baseline forged aluminum FLCA assembly. A current production OEM FLCA assembly (Figure 17-1) was used to establish the baseline for package, performance, mass, and cost.

The overall project design targets were:

- Structural Performance – Equal to, or exceed the baseline and OEM requirements.
- Mass – Less than, or equal to the baseline.
- Package – Meet available packaging constraints.
- Corrosion – Meet OEM corrosion requirements.
- Cost – Reduced vs. the baseline (target 30%).

The objective was to develop minimum mass designs within the packaging constraints that met the structural performance targets. Corrosion requirements were addressed by appropriate selection of material coatings, which typically did not add significant mass, but can increase cost. Mass and cost were the primary outputs of the study.

The results of the study support the following conclusions:

- The Clamshell Design is predicted to have equivalent mass to the baseline assembly with up to a 34% cost reduction potential at a production volume of 250,000 vehicles per year. The design is deemed production feasible based on forming simulations and industry welding examples (Figure 17-2).
- The I-Beam Design is predicted to have the highest buckling resistance and high stiffness with a 2% (0.05 kg) higher mass than the baseline assembly, with up to a 21% cost reduction potential at a production volume of 250,000 vehicles per year. The design is deemed production feasible based on typical welding process development and industry tube bending examples (Figure 17-3).
- The Forged Design is predicted to have the highest stiffness and durability performance (no welds) of all designs with a 4% (0.13 kg) higher mass than the baseline assembly, assuming an aggressive 3mm minimum gauge manufacturing target. It is recommended that the forging industry evaluate the manufacturing feasibility of the current assumptions, propose further design optimization opportunities, and determine the associated manufacturing costs (Figure 17-4).

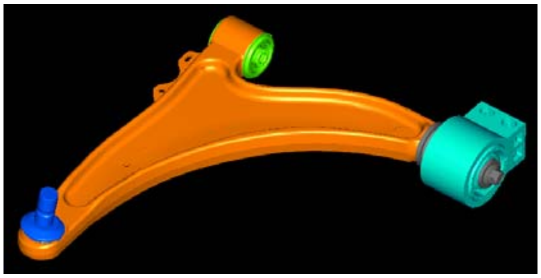

Figure 17-1. Baseline OEM FLCA Assembly

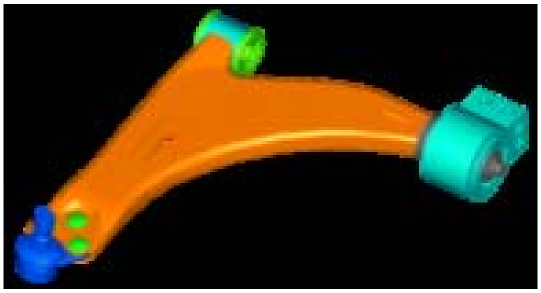

Figure 17-2. Stamped Clamshell Design

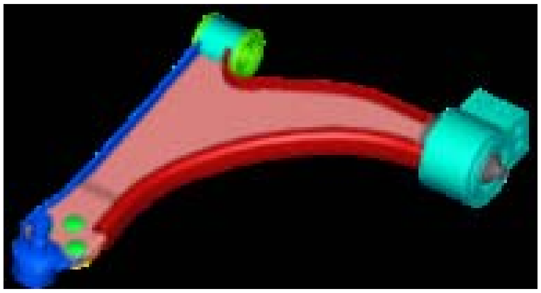

Figure 17-3. I-Beam with Tubular Flange Design

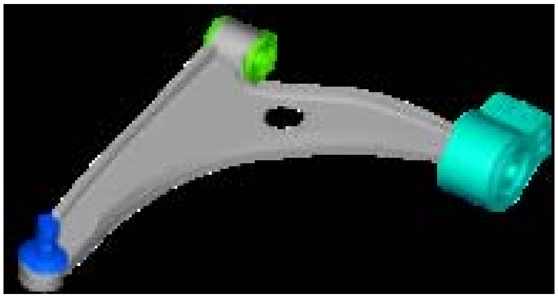

Figure 17-4. Forged Steel Design

17.3 Deliverables/Products Developed

- Lightweight sheet and forged steel proof-of-concept FLCA designs meeting following targets.
  - Structural performance
  - Cost
  - Mass
  - Corrosion
  - Packaging constraints
- Three designs (two sheet steel and one forged) developed:
  - Clamshell design
  - I-beam design
  - Forged design

17.4 Technology Transfer Activities

17.4.1 Proprietary Reporting

- ASP Offsite Presentation, 2010.

17.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

18. Precision Flow Form Application Development (ASP350)

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- Tech Knowledge

Project Duration: July 2009 – Present

18.1 Executive Summary

Flow forming is one of several types of metal spinning techniques used to produce round sheet metal products. Metal spinning has been known and evolving for centuries. All metal spinning processes use the same basic tools to shape metal. These tools include: a lathe-type spinning machine, rollers and a mandrel. The work piece, or blank, is normally a flat metal disc or pre-form that is clamped between the mandrel and the machine's tail stock. Rollers are used to apply pressure to the rotating blank forcing it, in successive passes, to take the shape of the mandrel which is made to the inside dimensions of the part.

Flow forming, a more recent advancement in the technology, elevates metal spinning to a higher plateau. It differs dramatically from other types of spinning in that, rather than shaping the metal by bending or compressing it, the metal is shaped by being forced to flow along the mandrel. Because of the high forming pressures involved, temperatures at the roller-workpiece interface typically are 1,000°F or higher, causing the metal to soften and flow; hence the name flow forming. Because the process changes the structure of the metal, drastic reductions in wall thickness can be achieved along with very fine accuracy.

The American Iron and Steel Institute (AISI) and Ford have done concept feasibility work on the precision flow form technology for a heavy duty F Series truck application. The study associated with this work indicated an estimated weight savings for the differential case of 59% in a bolted design (direct replacement for the cast design). In a welded design the weight savings would have been even higher and a half pound of bolts could have been eliminated as well. In addition, the potential existed to reduce the package size to deliver the same torque or increase the torque in the same package size.

The goal of this proposed project is to develop and demonstrate the precision flow form process of forming steel components to replace cast iron components to reduce weight by over 50% with equal or reduced manufacturing costs and significantly reduced tooling costs. The target component is a differential case housing.

Designed experiments will focus on developing the precision flow forming of distortion free, functional cases and on a distortion free welding process.

18.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

A Statement of Work (SOW) has been developed. The tasks outlined in the SOW are:

1. Launch and establish test criteria.
2. Design differential case and tooling.
3. Build tools.
4. Acquire materials.
5. Flow form process development.
6. Welding process development.

7. Assemble differential cases.
8. Validation testing.
9. Information dissemination and reporting.

It is planned to do the development work at Linamar, a recognized leader in the application of flow form technology in North America and a supplier of differential cases as well. They have excellent state-of-the-art development and tooling facilities in Guelph, Ontario ideal for this project. Linamar will access a large, high-pressure state-of-the-art flow form machine to develop this technology.

The benefits of successful completion of the proposed work can be applicable to all vehicles produced. The benefits include:

- Weight savings of 3-5 lbs. in target component in rotating mass for each differential case, (22-24 lbs. in heavy duty truck).
- Significant tooling cost savings and shorter tooling design and fabrication phase.
- Improved material yield versus ductile iron castings.
- Near net part resulting in less machining, less chips, less machining fluids, etc.
- Totally recyclable product (all steel).
- Potential improvement in balance and noise, vibration and harshness as a result of constant wall thickness and near net shape capability.
- Applicable to components such as coupling yokes for constant velocity joints and universal joint housings.
- A clear path to commercialization through a leading differential case supplier participating in the project.

18.3 Deliverables/Products Developed

- After successful completion through the three project gates, the work is expected to result in a differential case that can be "dropped" into an existing Ford drive train and perform equal to the current design with a 50% or more weight savings in the case.
- A study report that will identify operating and tooling costs compared to the current design.
- A finite element analysis for the proposed design to distribute to the team for improved technology transfer and understanding.

18.4 Technology Transfer Activities

18.4.1 Proprietary Reporting

- Talks at A/SP Offsite, October 2010.

18.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

19. Lightweight Rear Chassis Structure (ASP601)

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- Experi-Metal, Inc.
- Martinrea International
- Altair Engineering
- ArcelorMittal
- General Motors Company
- Ford Motor Company

Project Duration: July 2005 – August 2009

19.1 Executive Summary

A typical vehicle has about one-third of its weight in the body, one-third in the chassis and one-third in the powertrain. Considerable work has been done to reduce the weight of the body through the application of advanced high-strength steel (AHSS). The Auto/Steel Partnership (A/SP) recognized that a similar effort should be undertaken on the chassis. Thus, it implemented the Lightweight Rear Chassis Structure Project. The objective was to obtain a 25% mass reduction through the use of AHSS and the use of new chassis architecture.

The Auto/Steel Partnership's Lightweight Chassis Structures Project Team formed a Corrosion Working Group to address corrosion protection for chassis structures with thin steel members. In order to achieve mass reduction, the team planned to use thin, AHSS in a clean sheet design. However, in chassis structures, the thickness of the steel is used as a second line of defense against corrosion. Thus, thin steel could cause corrosion problems.

The Corrosion Working Group reviewed current practices. It concluded industry experience indicates that e-coat and supplemental corrosion protection methods may be used for certain designs with parts < 2.0mm in thickness. For example, the use of coated sheet steel (galvanneal or galvanized) for thin parts followed by e-coat on the entire chassis structure may be used, dependent on part location and chassis design, to prevent corrosion from reducing steel thickness to an unacceptable level.

The Chassis Structures Team thought it would be useful to have an alternative method of providing enhanced corrosion protection to chassis structures with thin steel. For this reason, the team asked the Corrosion Group to evaluate the use of the electropoli coating that is used in Europe. In simple terms, the process is pickling and fluxing a fabricated part followed by drying at 120°C and galvanizing at 450°C.

To evaluate the electropoli coating, the Corrosion Group compared the corrosion resistance of an electropoli coated chassis structure to an e-coated chassis structure. The main method used in the evaluation was the General Motors Corporation Trailer Test. The Working Group concluded that the electropoli coating provides significantly better corrosion (red rust) protection than e-coat and it may be used to protect chassis structures with steel members < 2.0mm thick. However, the Working Group issued three cautions: the electropoli coating adds about 5% to the mass of a chassis structure; the electropoli process may temper the martensite in AHSS, thereby lowering its tensile and fatigue strengths; and the electropoli coating holds dirt, which might be unacceptable where visible.

19.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The Lightweight Rear Chassis Structures Project Team selected a rear-wheel drive donor vehicle for the baseline chassis (Figure 19-1). As the first phase in its project, the team optimized the materials in the rear chassis and built 10 prototypes for various types of testing (Figure 19-2). Two of the prototypes were provided to the Corrosion Working Group.

Evaluation of Electropoli Coating System:

In order to evaluate the electropoli coating, the Corrosion Working Group had four chassis structures coated by electropoli in France: two baselines and two Phase I prototypes.

One baseline (e-coated), one electropoli coated baseline and one electropoli coated Phase I prototype were sectioned to check coating coverage. For the two electropoli coated chassis structures, sectioning also allowed a check to determine if the coating process had any effect on the mechanical properties of the steel components.

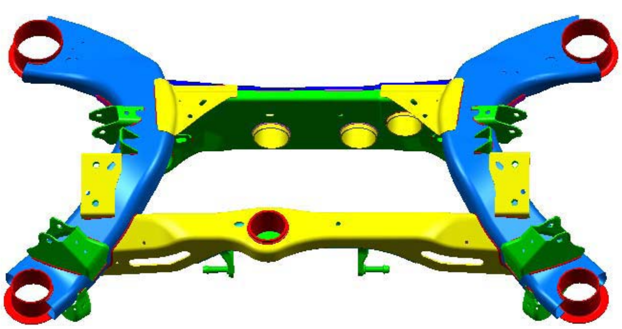

Figure 19-1. Baseline Chassis Structure

Figure 19-2. Phase I Prototype

General Motors Company corrosion tested the remaining two electropoli coated chassis structures using its trailer test. A baseline chassis structure with e-coat was also trailer tested. These three chassis structures were sectioned after trailer testing. The performance of the electropoli coating was obtained by comparing the electropoli coated sections to the baseline (e-coated) sections because the baseline's corrosion performance in the field is a known entity.

The conclusions reached by the project were:

1. Industry experience indicates that e-coat and supplemental corrosion protection measures may be required for certain designs with parts < 2.0mm in thickness. For example, the use of coated sheet steel (galvanneal or galvanized) for thin parts and e-coat for the entire chassis structure may be used, dependent on part location and chassis design, to prevent corrosion from reducing steel thicknesses to an unacceptable level.

2. Hot dipping a chassis structure using the electropoli process provides significantly better corrosion (red rust) protection than e-coat. This method could be used to protect chassis structures with members < 2.0mm thick. However, the following cautions should be considered:

a. The current electropoli coating is heavier than required solely for corrosion protection. It adds about 5% to the mass of an arc welded chassis structure.

b. The electropoli hot dipping process may temper the martensite in steel thereby lowering its tensile and fatigue strengths.

c. The electropoli coating holds dirt, which cannot be removed with normal rinsing. The dirty appearance might be unacceptable where visible (e.g. wheel wells).

19.3 Deliverables/Products Developed

- 10 prototype chassis structures coated in e-coat or electropoli for evaluation in corrosion studies.

19.4 Technology Transfer Activities

19.4.1 Proprietary Reporting

- Presentations at A/SP and USAMP Offsites.

19.4.2 Non-Proprietary Publications and Proceedings

[1] Non-proprietary reports are posted on the Auto/Steel Partnership website, www.a-sp.org.

1. Multi-Materials Vehicle Program Overview (MMV701)

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Team Members:

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- Chrysler Group LLC
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- Multimatic
- TRC/NCMS

Project Duration: June 2007 – September 2010

1.1 Executive Summary

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

The MMV R&D portfolio emphasized design, joining, corrosion, energy management, manufacturing processes, and other technologies that could facilitate mixed material systems that could support delivery of FreedomCAR goals by 2015. Recently MMV expanded to analyze the weight reduction required for a 7-passenger minivan and an 8-passenger crossover utility vehicle (CUV) to meet 40% and 25% fuel economy improvements respectively without degrading vehicle performance while using currently available gasoline engine and transmission technology.

The MMV team focused on analytical, design, cost modeling and benchmarking studies supporting the three "seed project" technologies. Longer term focus of future MMV projects within other USAMP groups will be on integration and joining/assembly technologies and associated process developments for manufacturing discrete parts and sub-assemblies in high-volume.

The majority of the MMV efforts focused on supporting the three "seed projects," the Auto/Steel Partnership (A/SP) Future Generation Passenger Compartment design and optimization project, the Advanced Metals Division (AMD) Magnesium Front-End Design and Development project, and the Automotive Composite Consortium (ACC) Composite Underbody project. Three of the five MMV projects (701, 702, and 703) provided the vehicle engineering metrics, the baseline CAD and CAE analyses and the baseline cost model against which the alternative material project teams could compare their designs. This effort provided the consistent foundation for the three "seed projects" and formalized the metrics and costs.

The final project from the MMV team identified weight savings required to meet fuel economy while maintaining critical full vehicle performance metrics such as zero to sixty miles per hour acceleration time and trailer tow grade capacity. With the currently available modern engines significant weight must be reduced from current vehicle to meet future fuel economy metrics. This project did not identify how the weight could be reduced from the vehicle or if the resulting vehicle architecture could meet all the Federal safety requirements and typical customer durability requirements. This effort provided insight into the required weight saving for two levels of fuel economy improvements.

1.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Objectives:

- Conduct collaborative, pre-competitive, high-risk research to develop the component technologies and direct R&D in materials and processes that enable the high-volume production MMVs that are half the mass, as affordable, more recyclable, and of equal or better quality and durability.
- Connect and relates the USAMP's A/SP, ACC, and AMD projects together in a MMV so that USAMP projects address vehicle level material integration issues as well as bulk materials issues.
- Establish Vehicle Technical Specifications (crash performance, dynamic stiffness, durability, etc.) for donor/baseline vehicle for alignment of other USAMP projects.
- Archive the CAD and CAE models and analyses for the baseline donor vehicle and from each of the three "seed" projects for alignment of other USAMP projects.
- Establish baseline cost estimates for the steel baseline donor vehicle for alignment of other USAMP projects.
- Determine weight reduction required, using vehicle performance/fuel economy simulation analysis, to enable a current production 7-passenger minivan and an 8-passenger CUV to achieve fuel economy improvements of 40-45% and 20-25% respectively, when retrofitted with smaller current production 4-cylinder engines and state-of-the-art transmissions, while maintaining the performance metrics of the current production vehicles.

Accomplishments:

- Selected a donor/baseline vehicle platform to serve as a benchmark to quantify and compare technology improvements. The vehicle was a General Motors large rear-wheel drive passenger vehicle. (FY 2007)
- Created the MMV Technical Specification metrics for safety, ride and handling, durability, noise, vibration and harshness (NVH), recyclability, serviceability, manufacturability, as well as selected vehicle use scenarios such as towing and shipping tie down. (FY 2007)
- Provided the CAD and CAE models plus the baseline vehicle analytical performance for the donor vehicle to the other teams. Archived the CAD and CAE files for the baseline vehicle and the analyses. (FY 2008)
- Archived the CAD and CAE file from the three "seed project" alternative material designs for the A/SP steel passenger compartment, the AMD magnesium intensive front-end and the ACC composite underbody. (FY 2010)
- Provided the baseline cost model and requisite assumptions for determining the costs of the donor/baseline steel vehicle. The predominantly stamped steel baseline vehicle costs included part costs and assembly costs plus the investments required for both the parts and the assembly. These costs were used by the other USAMP projects for comparisons with the alternative material designs. (FY 2009)
- Analyzed the weight reduction required, based on analyses of vehicle performance and fuel economy analyses, to achieve the targeted 40-45% and 20-25% desired fuel economy improvements (for a 7-passenger minivan and 8-passenger CUV respectively) while maintaining performance comparable to the current production

vehicles. For the two vehicles evaluated in this project, a 7-passenger minivan and an 8-passenger CUV weight reductions between 11% and 50% are required, depending on aero improvements and engine technology, to meet the targeted 40-45% and 20-25% fuel economy improvements while maintaining performance in six customer driven metrics. (FY 2010)

1.3 Deliverables/Products Developed

- MMV Technical Specification.
- CAD/CAE Models for donor vehicle obtained and achieved with Multimatic.

1.4 Technology Transfer Activities

1.4.1 Proprietary Reporting

- USAMP and DOE Reports and offsite presentations.

1.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

2. CAE Baseline Development & Cost Modeling for "Seed" Projects (MMV702 & MMV703)

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- Camanoe and Associates
- Multimatic

Project Duration: 2007 – September 2010

2.1 Executive Summary

The donor vehicle platform, the GM unibody (body-frame-integral) rear-wheel drive vehicle, has formed the baseline for the lightweighting technology improvements. The focus for the three initial technology "seed projects" addressing major lightweighting initiatives are: A/SP's Future Generation Passenger Compartment (FGPC), AMD603 Magnesium Front-End Design and Development (MFEDD) and ACC007 Composite Underbody (ACCU). For FY 2010, the focus was on archiving the design information and engineering performance of the alternative material vehicle structures.

2.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

This project used a supplier, Multimatic as the archivist for the design information and engineering performance analyses from the three "seed projects." Multimatic stored all of the data from the baseline vehicle and the three "seed project" alternative material designs. The archive included CAD files and CAE models and selected analyses for the baseline steel vehicle as well as the high-strength steel passenger compartment, the magnesium intensive front-end and the composite underbody. These archived CAD and CAE files will be available to USAMP projects for seven years.

The archived information included the CAD from the baseline steel vehicle plus the CAD information from the three alternative materials "seed project." Figures 2-1, 2-2 and 2-3 show the designs.

Figure 2-1. Auto/Steel Partnership (A/SP) Future Generation Passenger Compartment (FGPC) Design

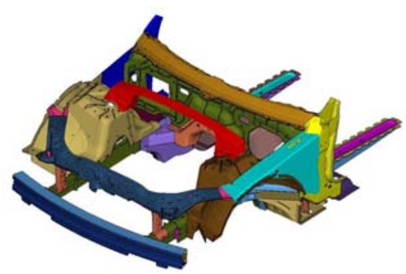

Figure 2-2. Advanced Metals Division (AMD) Magnesium (Intensive) Front-End Design

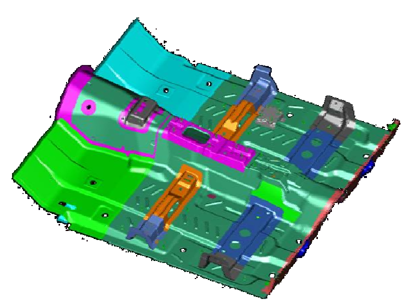

Figure 2-3. Automotive Composites Consortium (ACC) Composite Underbody Design

The CAE archive included the safety, durability and NVH models and selected load cases for the baseline steel vehicle plus the three alternative materials "seed projects."

Project completion in FY 2010 archived the design and engineering analysis information from the baseline steel vehicle plus the three alternative materials "seed projects."

<u>MMV Baseline Cost Model Development</u>

Camanoe and Associates developed the MMV Baseline Cost Model. Camanoe estimated the piece costs, assembly cost and investment for the donor vehicle baseline body-in-white. The establishment of the cost model analysis as a single project through MMV minimized the work and costs to each of the three "seed" projects.

The results include cost estimates for the stamped steel baseline donor vehicle from the technical cost modeling analyses. Specifically, the cost of each individual part has been modeled based on the material and manufacturing technique, i.e. typical stamping operations. The modeled part costs include the material, forming, labor, energy, consumable materials, overhead and amortized costs from the tooling, equipment and facilities. The analysis assumes 100,000 vehicles per year production rate. Also, the analysis assumes that the tooling for each part is amortized over five years. Additionally, the investment costs for both the part production and the assembly have been estimated using technical cost modeling.

2.3 Deliverables/Products Developed

- Design and engineering analysis.

2.4 Technology Transfer Activities

2.4.1 Proprietary Reporting

- None at this time.

2.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

3. Multi-Material Metallurgical Bond Joining to Steel (MMV704)

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- General Motors Corporation
- DaimlerChrysler Corporation
- Oak Ridge National Laboratory (ORNL)

Project Duration: October 2007 – March 2009 (original completion date prior to early termination)

3.1 Executive Summary

The primary objective of this concept feasibility project was to verify that the proposed technology can achieve a true metallurgical bond between cast aluminum and steel and between cast magnesium and steel. There are no known alternative, economically attractive processes that can achieve a true metallurgical bond. Successful development of this technology will provide a means to bond steel flanges to cast components such as shotguns, thus allowing for existing, low cost spot welding joining solutions. This technology will permit multi-material sub frames (castings and hydro forms) to be manufactured without risky, massive mechanical locking/joining solutions or expensive non-traditional welding solutions.

The processes for joining multi-material components (aluminum, magnesium and steel) into vehicle structures often add cost and offset weight saved from the use of the lighter weight materials. Capital costs may be increased to implement non-traditional welding processes, machining processes, fastener assembly stations, associated material handling systems, etc. Operating costs also increase due these added processes and added parts. In addition, some of the mass reduced by using the lighter weight materials is offset by added locking features, bolts, bolt bosses, flanges and other features.

Recent investigative developments at ORNL have shown that it is possible to achieve a metallurgical bond between aluminum and steel or magnesium and steel by applying ultrasound to steel inserts in molds for casting of the lighter metals. The initial work seemed to indicate that there was no significant loss in productivity due to the introduction of the insert or ultrasound. However, significant development and testing is needed to verify these assumptions and identify the risks and opportunities for application of this technology.

3.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The existing body of investigative work performed by ORNL demonstrated a potential breakthrough in achieving a metallurgical bond between dissimilar materials, but was insufficient to evaluate the true potential or identify the critical process parameters. The approach proposed in this project included:

- Project team will create test criteria and identify potential target applications.
- A test piece casting will be designed for selected steel inserts that meet the test criteria.
- ORNL will develop the process for and manufacture the test castings.
- The cast components will be tested according to the test procedure and analyzed by the team.

The project intended to use the development foundry at ORNL for the proposed work. Successful completion of this concept feasibility project will include identification of technical hurdles and plans for any follow-on work to overcome them.

The project was terminated in December 2007 by mutual consent between USAMP and DOE-ORNL.

3.3 Deliverables/Products Developed

- None.

3.4 Technology Transfer Activities

3.4.1 Proprietary Reporting

- None.

3.4.2 Non-Proprietary Publications and Proceedings

- None.

4. Lightweight 7+ Passenger Vehicle (MMV903)

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- FEV, Inc.
- Multimatic
- Chrysler Group LLC
- General Motors Corporation

Project Duration: October 2009 – September 2010

4.1 Executive Summary

The goal of the Lightweight 7+ Passenger Vehicle simulation project was to determine the weight reduction necessary to achieve fuel economy improvements of 40-45% and 20-25% for a baseline minivan and up-level crossover utility vehicle (CUV), respectively. Vehicle performance and towing capacity were not to be compromised from the current vehicle's capability. The project focused on a lighter weight vehicle, a reduced power engine, high-efficiency transmission, reduced auxiliary loads, and improved aerodynamics. This project supported the overall MMV goal of identifying the weight reduction opportunities to achieve fuel economy improvements while maintaining vehicle capabilities.

This final project of the MMV effort documented the weight saving required for a 7-passenger minivan and an 8-passenger CUV to meet a 40% and 20% fuel economy improvement while maintaining current vehicle performance metrics. This effort identified the substantial weight reductions required, 11% to 50%, even with improved aerodynamics and the best current production engines and transmissions to meet the fuel economy and performance targets.

It is important to note that this study did not consider how the weight reductions could be achieved or if the resulting vehicle would meet the necessary safety, durability, NVH, vehicle dynamics and other metrics. Additionally, this project did not address the cost and manufacturing implications of the suggested weight reductions.

4.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

The baseline vehicles selected for this study were a MY2010 Chrysler Town & Country minivan and an up-level MY2010 Chevrolet Traverse FWD, CUV. Two engine selections were made for each vehicle (total of four engines), each with different peak power ratings. Using the vehicle simulation software GT-Drive by Gamma Technologies, the simulation models were first correlated to the two reference vehicles, with their standard production powertrains, for both fuel economy and performance.

Next, the models were updated with the newly selected powertrains, various transmission gear ratios and shift schedules, reduced auxiliary loads, and improved aerodynamics. An iterative weight reduction process was subsequently conducted. The vehicle was simulated at three distinct starting (prior to weight reductions) weight classes. The EPA equivalent test weight (ETW) is classified as the vehicle base curb weight plus an additional 300 pounds. The gross vehicle weight rating (GVWR) is the vehicle curb weight plus additional passengers and luggage. The gross combined weight rating (GCWR) is the GVWR weight plus additional weight to account for trailer towing. A total of 480 unique vehicle models were simulated during the course of the analysis. The vehicle response curves versus vehicle weight for each powertrain were developed for each of six performance metrics at the appropriate vehicle weights. Additionally, the effects of improved aerodynamic designs were investigated by reducing the drag by 19% for the baseline minivan and by 6% for the up-level CUV.

The six performance criteria required of the newly configured vehicles were four acceleration tests (five-second distance, 0-30 mph, 0-60 mph, and 0-100 mph), hill climb ability at 55 mph, and top speed. The newly configured vehicles had to meet or exceed the current production vehicle's performance in these six customer relevant performance metrics.

The final results reveal that a significant amount of weight reduction is generally needed to achieve the desired fuel economy targets while maintaining performance comparable to the current production vehicles. For example, the baseline minivan with a curb weight of 4,507 lbs. getting 24.3 mpg must be weight reduced by 2,250 lbs. to a new curb weight of 2,257 lbs. to reach a fuel economy of 34 mpg using the 2.4L I4 engine with original baseline aerodynamics.

The fuel economy goal for the baseline minivan was to achieve an improvement of 40-45% over the 2005 segment average of 24.3 mpg. This is the EPA combined "raw" fuel economy result from the FTP75 (city) and HWFE (highway) drive cycles, and then weighted based on 55% city and 45% highway driving mix. These fuel economy numbers are not the same as what is posted on a new vehicle sales sticker ("label") or in literature. The "raw" versus "label" fuel economy numbers can vary significantly due to supplemental cycles that account for air conditioning use and more aggressive highway speed and acceleration.

In conjunction with the fuel economy predictions, performance simulations were conducted.

The analyses began by matching the modeled vehicle performance for both the baseline minivan and the up-level CUV against published and proprietary performance data. Once the vehicle simulations with the software GT-Drive by Gamma Technologies was in agreement with the vehicle performance the models were updated to include the new engines and dual clutch six-speed transmissions. Then the effects of low rolling resistance tires and reduced auxiliary loads were included in the models. At this point the effects of these improvements before any weight reductions were evaluated.

For the baseline minivan, the switch to the 2.4L I4 naturally aspirated engine alone achieved a 10% improvement in combined fuel economy. The transmission was the second best fuel economy enabler followed by the reduced auxiliary loads and then the low rolling resistance tires. Final fuel economy of this configuration improved 20% over the baseline vehicle. But peak power compared to the original 3.8L V6 was ~23% less so performance will suffer and the accompanying 0-60 mph time increased over two seconds. Overall fuel economy improved 29% before any weight reductions. Vehicle weight reductions would then gain back the lost performance.

4.3 Deliverables/Products Developed

- Weight reduction targets for Minivan and CUV.
- Data on Design Study.

4.4 Technology Transfer Activities

4.4.1 Proprietary Reporting

- None at this time.

4.4.2 Non-Proprietary Publications and Proceedings

[1] Zaluzec, M.M. and Wagner, D.A., Multi-Materials Vehicle R&D Initiative, Project ID LM009, 2010, DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, June 7-11, 2010, Wardman Park Marriott Hotel, Washington, DC.

1. Non-Destructive Inspection of Adhesive Metal/Metal Bonds (NDE601)

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- Dow Automotive
- Henkel Corporation
- Lord Corporation
- Thermal Wave Imaging
- NDI Solutions
- Olympus NDT
- DaimlerChrysler Corporation

Project Duration: 2006 – 2008

1.1 Executive Summary

Adhesive bonding is an important joining tool for modern automotive structures. Structural adhesives can greatly increase the strength as well as stiffness of joints and can significantly improve the crash performance of vehicles. Structural adhesives also allow more efficient structures to be designed that may be difficult to weld. Structural adhesives will play an increasingly important role in the joining of dissimilar materials such as aluminum to steel or magnesium to other metals: the adhesive acts both as a galvanic barrier and as a stress spreader on materials that are more brittle.

The NDE601 project was directed at filling a major technical gap for adhesives: how to determine whether an adhesive bond on a vehicle would perform as designed without actually destroying the bond – how to non-destructively inspect (NDI) the adhesive and assure that the bond had its designed strength.

The major goal of the first phase of this project was to select and develop an NDE method to inspect automotive flange joints when the adhesion was good. After evaluating several alternatives, ultrasonic pulse/echo inspection with a manually scanned linear array was targeted as a near-term solution. A unique phased-array probe system with a closed-loop circulation system was built by the team and successfully passed testing on over 150 flat coupons. Over 100 m of adhesive bonding were imaged.

During the second phase, the evaluation of this first generation ultrasonic array system was completed. In this round, all the adhesive bonds on three production car bodies were subjected to inspection. This allowed issues of inspection plan organization, report generation, access-ability, ultrasonic coupling, operator skill, and operator ergonomics to be evaluated. The system performed quite well delivering high-resolution images of the adhesive area, perhaps the most important element of needed inspection.

In this project verification of the wedge peel method as a new, high-spatial resolution method was completed that could quantify the variation of bond strength along long bond lines and with the presence of contaminants. Results showed that ultrasonic measurements can accurately predict wedge peel strengths.

Based on the performance of the Gen I probe, a second ultrasonic probe system was designed specifically for automotive adhesive bond inspections. This was targeted as a production-intent system. This custom array and probe were built, assembled, and tested and shown to significantly improve accessibility and reduce system cost.

Extensive work was also completed on bonds that have intimate contacts but are weak – so-called kissing bonds. Several new contaminates, in addition to grease, were shown to reproducibly reduce bond strength. It was shown that grease reduces both shear and tensile strength with the same sensitivity dependence and that grease contamination can be detected with ultrasonic pulse/echo inspection. A large suite of coupons with reduced bond strengths were built for a round robin test of advanced inspection methods.

Steady progress was made on the project objectives during the second full year of funding. The first generation linear ultrasonic array tool for off-line inspections was successfully tested on production vehicles. While this ultrasonic array system is currently only able to inspect the wet-out on the outer skin, the system performance appears to be adequate to allow the adhesive mapping. The second-generation version of this ultrasonic array scanner is now been built and is the final prototype development. It improves the performance on narrow flanges and on curved surfaces. The high-resolution wedge-peel test has been established as a bond strength standard. Simple scaling laws allow NDI measurements of bond width and thickness to predict the bond strength over a wide range of conditions. Finally, promising results were obtained from the USCAR transferred technology to SNL to produce weak-bond samples.

1.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Objective:

The goal of this project is to identify and develop one or more NDI methods for adhesive bond evaluation to be used in an automotive manufacturing environment that would foster increased confidence and use in adhesive joining. The wider use of adhesive joining could result in reduced vehicle weight, increased body stiffness, and improved crashworthiness. Adhesives are also seen as a critical enabler for the joining of dissimilar materials in order to avoid corrosion from dissimilar metals.

- To accomplish this goal, the various attributes that determine the *bond strength* were identified along with an NDI method to measure that property. The success of this approach would be quantitative correlations of NDI to measured *bond strengths*.
- The target methods must be able to perform the inspection on the plant floor in at least an off-line audit time-window and be able to inspect most of the adhesive bonds on current production vehicles.

Accomplishments:

- The team completed the evaluation of the first generation array and probe holder on three body-in-white (BIW) structures. The BIW evalutions involved constructing inspection plans, inspecting over 100 beads with a wide variety of geometries and probe orientations, and generating evaluation reports. Over 80 % of the adhesive structure could be imaged at a speed of over 1 m/min with this feasibility system. These images elucidate large-scale features such as adhesive spread and the fill-factor of the flange. The 1-mm resolution also allows small features such as surface springback, air entrainment, bead dribbles, and weld expulsion damage to be imaged.
- The project team designed, built and evaluated a second generation ultrasonic array and probe holder that is intended as a production prototype. This device is simpler and smaller than the first generation and should be able to inspect 95% of the BIW while imaging 85% of the area under the probe. The system works with a commercially-available closed-loop

water circulation system and should have a significantly reduced system cost.

- A new signal-processing effort was initiated to reliably extract the adhesive thickness from the ultrasonic array echo data. This analysis can rapidly compensate for probe to surface distance variations.
- The ability of ultrasonic inspection to accurately predict the bond strength was tested. On flat coupons, non-destructive measurements of the bond area and the bond thickness can predict the strength to within 10% over 90% of the adhesive bead. The primary shortcoming is that the scaling law presently *underpredicts* the bond strength at the beginning of the adhesive bead. This is the area where the peel crack is initiated.
- Reproducible procedures for constructing weak (kissing) bond samples using a wide variety of contaminates and controlled cures were established. Multiple sets (nine) of samples were produced with reduced shear strength. The strength ranges were from 10% to 100%. Two types of containments were added throughout the bond strength range. Over 150 strengths tests were completed to characterize the weak bonds. NDI evaluations using ultrasonic and other NDI methods were done. The resulting images could be correlated to the subsequent strength measurements. Some initial promising results were obtained from several methods but additional study is necessary before any conclusions can be made.

1.3 Deliverables/Products Developed

- Ultrasonic Array Scanner.

1.4 Technology Transfer Activities

1.4.1 Proprietary Reporting

- NDE601-FY2006 Annual Progress Report for DOE ALM, Joseph DiMambro and Dennis P. Roach-Sandia National Laboratories, Cameron J. Dasch-General Motors Research & Development, December 15, 2006.
- NDE601-FY2007 Annual Progress Report for DOE ALM, David G. Moore and Joseph DiMambro-Sandia National Laboratories, Cameron J. Dasch-General Motors Research & Development, December 12, 2007.
- NDE601-FY2008 Mid-Year Progress Report for DOE ALM, David G. Moore and Ciji L. Nelson-Sandia National Laboratories, Cameron J. Dasch-General Motors Research & Development, May 15, 2008.
- Dasch, C.J. et al., “Engineering Report on NDI of Adhesively Bonded Mild Steel Flat Coupons for USCAR /USAMP Project NDE 601 – NDI of Adhesive Metal Bonds,” February 15, 2008.
- Neal, S., “Final Report Phase 1: Developing Ultrasonic Signal Analysis Tools for Metal/Metal Adhesive Bonded Joints,” September 15, 2008.

1.4.2 Non-Proprietary Publications and Proceedings

[1] DiMambro, J. et al., Disclosure of Technical Advance, “Probe Deployment Device for Optimal Ultrasonic Wave Transmission and Area Scan Inspections,” February 20, 2007.

[2] Lazarz, K. et al., “Correlating Adhesive Bond Strength with Non-Destructive Test Methods,” Annual Meeting of the Adhesion Society, Austin TX, February 2008.

[3] Dasch, C.J., "Non-Destructive Inspection of Adhesive Bonds in Automotive Metal/Metal Joints (NDE 601)," USAMP Offsite Review, October 29, 2008.

[4] Dasch, C.J., et al., "Using Quantitative Ultrasonic NDE to Accurately Predict Adhesive Bond Strengths," Quantitative Non-Destructive Evaluation Conference, Chicago, IL, July 2008.

2. Enhanced Resonance Inspection for Light Metal Castings (NDE701)

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- General Motors Corporation
- DaimlerChrysler Corporation
- Pacific Northwest Laboratory
- Citation
- Quasar International
- Modal Shop
- Polytec

Project Duration: 2007 – 2009

2.1 Executive Summary

The ability to use resonance inspection (RI) for testing and flaw identification has long been something of a hidden desire for many. The RI technique is quick and very sensitive making it an ideal choice in production environments. This project set out to determine if it was feasible to make RI more usable in everyday testing. There are many ways this might be helped: decrease the required size of the training set; choose the frequencies to watch more intelligently; predict the sensitivity of the test to a specific feature; etc. Because of the complexity of the resonance structure in even simple parts, computer modeling of the RI process has been deemed intractable in many instances.

This project has shown that modeling the resonant behavior of simple parts is not only possible, but quite accurate. The simulated results were compared with the experimental results from three commercial vendors – The Modal Shop (TMS), Magnaflux Quasar and Polytec. The use of laser vibrometry resolves any ambiguities as to the actual mode shape present at a particular frequency.

During this project, there was great progress in casting real-world parts, experimental testing, and cooperation with and between commercial partners. Great strides were made in automating mode identification and in predicting accurate mode frequencies. Errors were found in the CAD model of the connecting rod part through the use of computed tomography (CT) inspection to generate 3D CAE meshes of the part directly from the CT scan data.

Calculations of the frequencies were carried out with both CAD and CT data. More importantly, a computationally efficient variational method to predict resonance shifts for porosity, slits (oxide film model) and slots (more crack-like model) were carried out and the results were most encouraging.

Finite element and variational-principles based computational methods can be used to accurate model and predict the natural frequencies and vibrational mode shapes of a real-world part. More importantly, a more realistic part with complex surface features yields better correlations between predictions and measurements because of the shorter wave length, i.e. higher frequency, needed to trigger any possible mode switches between the predicted and the measured frequency spectra.

2.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

Objectives:

- Satisfy the need for rapid, reliable NDE to ensure the structural integrity of light metal castings
- To assess the capability of modeling approaches to accurately predict the vibrational mode frequencies along with the variability of those frequencies
- To quantitatively evaluate the sensitivity of RI to anomalies of various types and sizes in various locations.

Accomplishments:

- Connecting rod testing completed.
  - Automatic identification of modes based on comparison of calculation and laser vibrometer measurements
  - Dimensional check of CAD model using CT – discrepancies found
  - Accurate prediction of mode frequencies
    - Calculations based on both CAD model and CT data
  - Extensive numerical testing of efficient variational method to predict resonance shifts for porosity and slits (oxide film model)
- Real-world part (automotive knuckle casting) testing and modeling completed
  - In-plant selection of parts
  - Resonance measurements of the parts by Quasar and The Modal Shop (in plant) and Polytec
  - Precision material property measurements (1 part in 10,000)
  - 3D measurements (1 part in 1,000) by computed tomography
  - Finite element natural frequency extraction of knuckle and mesh sensitivity study
  - Modal analysis and steady state dynamic analysis for knuckle casting
  - Correlation of predicted mode shapes between measured resonance peaks.

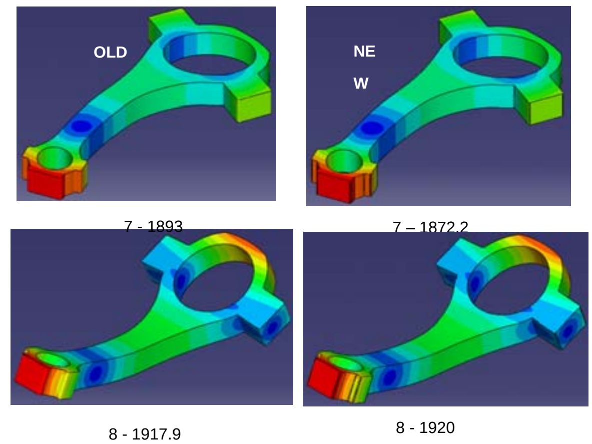

Figure 2-1. Comparison of Old and New Model Sizes on Resonant Modes - Low Frequencies

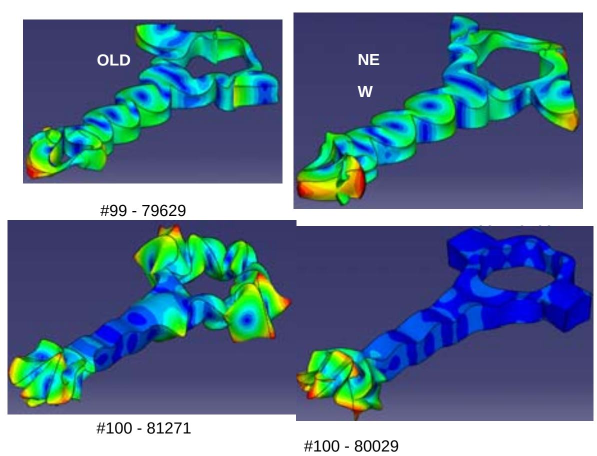

Figure 2-2. Comparison of Old and New Model Sizes on Resonant Modes - High Frequencies

2.3 Deliverables/Products Developed

- Modeling tools.

2.4 Technology Transfer Activities

2.4.1 Proprietary Reporting

- NDE 701: Enhanced Resonance Inspection for Light Metal Castings, AMD Offsite, Southfield, MI, September 27, 2007.
- NDE 701: Enhanced Resonance Inspection for Light Metal Castings, AMD Offsite, Southfield, MI, October 29, 2008.

2.4.2 Non-Proprietary Publications and Proceedings

[1] Dasch, C.J. et al., "Towards Quantitative Resonance Inspection: Resonance Mode Identification and Modeling," Review of Progress in Quantitative NDE 2008.

3. Reliability Tools for Resonance Inspection of Light Metal Castings (NDE901)

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- Oakland University

Project Duration: March 2009 – Present

3.1 Executive Summary

Resonance inspection (RI) is an emerging NDE technology that relies on detecting and interpreting the natural resonance frequencies of a part. It has potential to ascertain the structural integrity of cast metallic components with more accuracy, lower cost, and greater speed than currently used techniques. RI is used by several automotive suppliers of aluminum castings in programs that are monitored by Chrysler, Ford and GM. Applications include performance- and safety-critical parts. The current state of RI technology primarily relies on empirical techniques, the training time is long and requires large numbers of parts; furthermore, there is no clear criterion indicating when the training process is complete. Moreover, current RI techniques do not identify the anomaly location, size, or type when rejecting a part. Building on work from the previous concept feasibility project, this project seeks to make the implementation of RI quicker, easier, more precise, and to define a robust process to bring RI into use on most parts.

With improved quantification of RI, castings with significantly reduced mass could be brought into production.

In the concept feasibility project, it was been shown that RI responses to features of interest can be predicted using computer simulation tools. These tools included: methods to map material property inhomogeneity; a model to translate material properties and geometry into predicted frequencies; methods to identify mode shapes for each frequency, methods to predict the sensitivity of each mode to size and location of anomalies, and predictions of RI variability due to normal casting variation. This technical feasibility project seeks to enhance these tools and integrate them into an easy-to-use package and provide a standard process which can be followed by any organization. The new capabilities developed will include a sort module tool, a probability-of-detection estimator, and an inversion tool to indicate the most likely location of anomalies based on RI frequency shifts.

Results will be validated on the aluminum production chassis casting that was used in the earlier work. This part has moderate complexity typical for a chassis component while not being overly complex to facilitate computational analysis; small enough to permit x-ray tomography for corroboration; and manufactured from a well developed process which ensures an abundance of acceptable parts at low cost. RI sort modules will be made based on anomalies found in production.

3.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

RI is sensitive to structural anomalies that are currently difficult or impossible to detect non-destructively. Yet widespread acceptance has been hindered by the complexity of its training regimen; by its failure to identify reasons for rejecting parts; and by unknown sensitivity to anomalies. This project will address these shortcomings using modeling including typical material variations and casting discrepancies for a production casting.

This project is still open and in process. Based on the success of this project a new project may be proposed to make this technology commercially available. RI has the potential to be a cost-effective replacement of x-ray and fluorescent particle inspection.

3.3 Deliverables/Products Developed

- Establish a standardized and traceable procedure for production RI.
- Development of integrated (software) tools to predict the probability-of-detection of RI to performance-critical casting discrepancies.
- Development of tools to aid in the creation of sorting modules.
- Evaluation of the ability to identify anomaly type, size, and location from RI data.

3.4 Technology Transfer Activities

3.4.1 Proprietary Reporting

- Presentations at USAMP Offsites and DOE Reports.

3.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

4. Shearographic Non-Destructive Evaluation of Spot Welds for Lightweighting of the Vehicle (NDE1002)

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- Chrysler Group LLC
- Ford Motor Company
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Project Duration: May 2010 – Present

4.1 Executive Summary

The ultimate goal of this project is to develop a hybrid non-destructive evaluation (NDE) method to inspect resistance spot welds. In this project, an advanced optical technique, shearography, will be employed to measure full-field (2D) strain distribution on the surface of the weld. The measured data will be input into a finite element model (FEM) to generate 3D stress distribution and information about the weld nugget. The developed hybrid method can be implemented in mass production of automotive bodies. The NDE technology, based on the developed hybrid method is expected to be implemented on the production floor.

This project is open and still in progress.

4.2 Comparison of Actual Accomplishments with Goals and Objectives of Project

In the study, the best optical NDE technique and loading method, capable of detecting surface strain around the spot weld will be identified. Also, a finite element code will be developed to determine the nugget size using the surface strains measured optically. A number of welded coupons will be made to simulate various welding conditions. The coupons will be measured optically and evaluated using the FEM model. A correlation between the results of the measurements and the strengths of the welds will be established.

The method will include optical measurement of the weld and evaluation of the weld using FEM. The details of the optical measurement method and an FEM model incorporating experimental data will be developed. A correlation will be established between the measured results and the strength of the spot weld.

Commercial and/or plant floor implementation will be considered upon successful completion of this project.

4.3 Deliverables/Products Developed

- None at this time.

4.4 Technology Transfer Activities

4.4.1 Proprietary Reporting

- None at this time.

4.4.2 Non-Proprietary Publications and Proceedings

- None at this time.

Automotive Composites Consortium

		Prototype Lightweighted		Mass Reduction Achieved		
Project	**Technology Gaps Addressed**	**Vehicle/Component**	**Original Material/Mass (kg)**	**(kg)**	**(%)**	**Challenges/Gaps Still Remaining**
ACC 007 **Structural Automotive Components from Composite Materials (Focal Project 4)**	**1-** Design and analysis for structural (crash load carrying) composites has not been proven for automotive applications. **2-** Current automotive composite material and process systems are not designed to carry crash loads, and are not cost or cycle time effective. **3-** Structural joining of composites and metal structures.	GM early-development vehicle (Large Vehicle Underbody Steel Structures)	44.9	11.6 (floorpan) + 3.3 sled runner rail	26% floorpan only 31% w/ mass save from sled runner	**1-**-Components as molded were thicker, and thus heavier, than design. Fabrication modifications that would be needed to more accurately design and fabricate this structure need to be determined. **2-** Maximum weight savings are achieved with thickness and layup optimization, which may lead to complex preform layups. This increases the cycle time, and needs to be addressed. Possible solutions are automation, the use of multiple preform stations (which are inexpensive relative to the molding station), or a balance between weight optimization and complexity. **3-**-The weld bond structure needs to be made more mass efficient, and needs to be proven in a production scenario.
ACC 040 **Development of Manufacturing Methods for Fiber Preforms**	Design and fabricate a P4 preforming that can produce a handable net-shape pick-up box and tailgate preforms from glass or cabon fibers. Insure that the process can be conducted in a fast cycle time required for automotive capacity.	N/A (enable technology)	N/A (enable technology)	N/A	N/A	A full scale P-4 proforming appartus was designed, fabricataed, and refined for the prototype production of pick-up box and tailgate. The P4 appartus demonstrated the capability to produce handleable, net-shape/net-size preforms that exhibited low within-part and part-to-part areal density. The process is also capable of rapid cycle times and lower scrap rates for materials.

ACC 070 **Deformation and Environmental-Induced Degradation of Structural Automotive Composites**	This project resulted in the development of stress/strain test fixtures. The test fixtures were used to gain an understanding of the degree of degradation on a composite material from enviromental exposure sequences.	N/A (enable technology)	N/A (enable technology)	N/A	N/A	The stress/strain fixtures were designed, fabricated and used for investigation of composite material systems. Each OEM could use test fixtures to evaluate composite material systems being investigated for use on vehicle components.
ACC 080 Composite Intensive Body Structure (Focal Project 3)	**1 -** Design optimization and finite element analysis of the selected body-in-white structure. The structure met or exceeded all design requirements **2 -** P4 preforming technology for carbon fibers was developed, including the variation in wall thickness needed for mass optimization and the effect of carbon strand geometry on the preform uniformity. (with ACC 040) **3 -** SRIM molding technology for performs was developed. This was enhanced by flow simulations of the injection-compression SRIM **4 -** High-rate adhesive bonding technology allowing the structure to be assembled in a time acceptable in automotive production was achieved.		128 kg	86 (full design)	67%	**1-** Still need validation of crash modeling. **2 -** Preform uniformity still can be improved, particularly on vertical walls.

	5 - Structural testing of the asssembly shoed values consistent with those needed for the body-in-white, and closely mateched by the analytical predictions.					
ACC 100 **Predictive Technology Development & Crash Energy Management**	**1-** Coupled material-structural characterizations & testing protocols and procedures have not been developed for complex material systems. **2-** Predictive modeling and analysis tools based on first principles in mechanics and advanced computational methodologies for the analysis of the complex physics of quasi-static and dynamic crush have not been fully developed or validated for polymeric composites.	N/A (enabling technology)	N/A (enabling technology)	N/A	N/A	**1-** Recommendations on what tests are needed to fully characterize automotive composites still require more extensive studies. More in-depth testing procedures for size effects at higher loading speeds (e.g., 30-50mph) are needed. Proposed tests to characterize strain-rate effects as well as development of an atlas categorizing the morphologies of damage in FRC (especially textiles) still need further development. Develop standardized testing discriminators to aid in discerning between what constitutes a material property vs. a structural property are very much needed. Testing procedures to study environmental and in-service short- and long-term effects on the mechanical performance of structural composites also need developments and updates. **2-** Modeling the entire manufacturing process of a composite in order to predict its final (cured) in-situ mechanical properties is still at infancy and requires more extensive research and developments. Modeling methodologies that can predict the crush and damage patterns of fiber-reinforced composites still need further development, verification and validation. Models which can robustly include environmental and in-service effects on mechanical performance are needed. Computational technologies which can predict damage evolution and the final damaged state especially for the dynamic crush of a structural component/subassembly are still lacking maturity.

ACC 105 **Creep, Creep Rupture and Environment-Induced Degradation of Carbon and Glass-Reinforced Automotive Composites**	This project resulted in the development of tensile creep test fixtures. The test fixtures were used to gain an understanding of the degree of creep behavior on a composite material from enviromental exposure	N/A (enable technology)	N/A (enable technology)	N/A	N/A	The tensile creep fixtures were successfully used to measusre the creep performance of composite material systems. Resulting creep data generated could be used for evaluation of composite materials for each OEM.
ACC 205 **A Novel Fixture for Compression Testing of Composites**	This project resulted in the development of compression creep fixtures. The test fixtures were used to gain an understanding of compressive creep behavior of composite material systems.	N/A (enable technology)	N/A (enable technology)	N/A	N/A	The compressive creep fixtures were successfully used to measure the compressive creep behavior of composite material systems. Resulting creep data generated could be used for evaluation of composite materials for each OEM.
ACC 932 **Advanced Materials and Processing of Composites for High-Volume Applications**	**1-** Established manufacturing guidelines for eliminating visible distortions in production Class-A components are not fully developed. **2-** Existing carbon fiber SMC materials do not deliver expected value (low strength, high COV, high cost). Reduce Class-A Panel wall	1- Class-A Body Panels including deck-lids and Hoods. 2- OEM Body Panels.	N/A (enable technology) N/A (enable technology)	N/A N/A	N/A N/A	**1-** Implement Bond-Line –Read-Through manufacturing guidelines on current production component to demonstrate processes developed during project is robust and accurate. **2-** Key process parameters still need to be identified and controlled to provide a more consistent material. **3-** Performance evaluation of formulations developed for direct compounding require further validation with a broader range of testing including longer term durability. In addition rheological

	3- Low cost compounding methods for advanced high performance composites are not fully developed. Low cost Long Fiber Nylon Thermoplastic composite material	3- Ford B,C, and C/D Vehicles	N/A (enable technology)	N/A	N/A	characteristics and formulations needs to be reviewed for ease of processing.

Project	Technology Gap Addressed	Component benchmarked	Original Material/ weight of component (lb or kg)	Weight Reduction achieved (lbs or kg)	Weight reduction achieved (%)	Challenges still remaining
Structural Cast Magnesium Development (AMD111 & AMD112)	Magnesium cast structural components capable of 125^{o} C sevice temperatures situated in high corrosive areas of a vehicle.	Engine cradle	Al (16.36kg)	Mg AE44 alloy (5.5Kg)	34%	Effective, low cost galvanic corrosion mitigation techniques for Mg component corrosion protection.
Low-cost Powder metallurgy for Particle-Reinforced Aluminum Composites (AMD210 & AMD220)	Need for low-cost metal matrix composite components for high temperature powertrain applications. Particle-reinforced aluminum composite components manufactured from powder metallurgy processes evaluated as a means to close the gap.	N/A - Enabling technology				None identified.
Hydroforming of Aluminum Tubes (AMD233)	Need for increased confidence for designing aluminum hydroformed parts for automotive applications. The project has provided a wealth of data on material properties, process parameters, strain distributions and thickness distributions from hydroforming and bending of welded and extruded aluminum tubes. The bent tube inside and outside corner fill tests developed in this project have been used by other researchers interested in hydroforming. The simulation results have established that finite element modeling can be used to model the multi-stage bending and hydroforming operations with reasonable success.	N/A - Enabling technology				The project has established several areas that need further research. We would like to have more complete forming limit data, for example. This is especially true for the material that has been deformed during tube bending. Also, the issue of instability near failure during hydroforming is not well understood. Our simulation results suggest as well that better material models (i.e. yield surfaces) would improve modeling capability. The effect of the level of push assist during bending is another area that requires more work.

Flexible Binder Control System for Robust Stamping (AMD301)	Minimizing or eliminating the iterative process typically required to fine-tune stamping dies to produced defect-free parts, especially with respect to difficult to stamp aluminum, magnesium, and high strength steel alloys.	N/A - Enabling technology				Magnesium still not formable at room temperature even with extensive binder control. Need more efficient valves and controllers, more efficient and simplified hydraulic system, more efficient closed loop process controllers for friction and draw-in sensors, more efficient simulation/optimization codes to reduce computing tie for load-trajectory optimization. Need to develop criteria for best application of the technology and conduct a full-scale economic feasibility study, and need to develop plans with leading press manufacturers to retrofit, integrate, and implement hydraulic cushions in their presses.
Long-Life Electrodes for Resistance Spot Welding of Aluminum sheet alloys and Coated High-Strength Steel Sheet (AMD302)	Resistance spot welding electrodes wear out very quickly when welding aluminum or coated steels. This adds to cost and reduces quality. This project evaluated existing and developmental electrode material and geometry technologies to improve electrode life in production.	N/A - Enabling technology				While electrode life was improved for coated steels. No demonstrable plan was identified for improving electrode life when welding aluminum.
NDE Tools for Evaluation of Laser-Welded Metals (AMD303)	Ability to replace current manual destructive testing of laser welded sheet and structures in zinc coated and uncoated steel and aluminum with fast, accurate, robust, non-contact Non-Destructive Evaluation (NDE) tools and methodologies	N/A - Enabling technology				Personnel training in use of state-of -the art equipment, ability to automate.
Magnesium Powertrain Cast Components (AMD304)	Cost-effective mass reduction of cast engine components with demonstrated performance and durability: properties to enable design, castability, corrosion protection, acceptable NVH, successful engine test; linerless cylinder bores	V6 production engine	Fully dressed production engine (primarily Al) = 176.8 kg; Individual Al components: Cylinder block (32.2 kg), oil pan (4.4 kg), front	MPCC dressed engine (primarily Mg) = 13.8 kg ; Individual components converted to Mg: Cylinder block (8.2 kg); oil pan (1.2 kg); front cover (3.0 kg)	Fully dressed engine (including many parts not light-weighted) Al to Mg 7.8%; cylinder block 25%; oil pan 27%; front cover 56%	Mass reduction target was 15% for individual components; achieve 29%; identified no show stoppers (not corrosion, not NHV, not design or castability; and cost of mass reduction was $2.30 per pound (original target was $2); passed four engine tests; but failed bulkheads on high speed durability; FEA and failure analysis show that design modification could avoid this failure.

An Improved A206 alloy for Automotive Suspension Components (AMD305)	Higher strength aluminum casting alloy capable of replacing iron castings and aluminum forgings.	N/A - Enabling technology	Optimize 206 alloy chemical compositions, evaluate heat treatment and aging conditions beyond T4. Evaluate with processes beyond tilt-pour permanent mold. Perform cost analysis.
Plasma Arc Spot Welding of Lightweight Materials (Aluminum and Magnesium) (AMD306)	Lack of low cost joining processes for high volume light metal (aluminum and magnesium) applications.	N/A - Enabling technology	Phoshoric acid-based pretreatment prior to plasma arc spot welding required to eliminate haloes.
Warm Forming of Aluminum II (AMD307)	Developed die architecture and process to provide thermal stability / uniformity to minimize dimensional distortion during steady state production conditions	N/A - Enabling technology	Gap: Need to develop and demonstrate ***high volume*** warm forming process.
Exploratory Study into Improved Foramability and Strength of Automotive Aluminum Sheet Alloys with an Electric Field (AMD308)	Need for enhanced tensile strength and elongation AA6111-T4 sheet aluminum	N/A - Enabling technology	Scaleability of the process.
Aluminum Automotive Closure Panel Corrosion Test Program (AMD309)	Current auto industry accelerated corrosion tests focus on steel substrates and were tailored for that need. The team looked at existing industry test procedureds to develop one with good correlation to real world performance for aluminum.	N/A - Enabling technology	Two tests were identified to have good correlation with real world field exposure - ASTM G85 -A4 and ASTM G85-A2. Sulfur is often observed in the corrosion products from the on-vehicle exposures and while the exposure in ASTM G85-A4 insludes SO_2, use of SO_2 in the laboratory environment is often difficult.
Low-cost Powder Metallurgy for Particle Reinforced Titanium Automotive Components: Manufacturing Process Feasibility Study (AMD310)	Need for a low cost powder metal manufacturing process to obtain fully-dense particle-reinforced parts from commercial-grade titanium metal feedstock to enable low reciprocating-mass components for powertrain applications.	N/A - Enabling technology	Additional refinement of sintering cycle for Ti-MMC to improve properties in the full density condition to improve fatigue, fracture toughness, and corrosion resistance. Hydrogenated powder approach should be explored to improve cost effectiveness. Cost analysis should be conducted to evaluate cost effectiveness of developed materials and processes.

Springback Compensation Project for Advanced Sheet Forming Materials (AMD311)	The project addressed three critical technology gaps in compensating stamping dies for advanced sheet forming materials: (1). Developed and implemented geometric-based numerical algorithms to compensate a draw die from springback prediction. The iterative nature of the algorithm enabled the achievement of required dimensional accuracy; (2). Developed and implemented auxiliary numerical technologies for springback compensation, including trimline update, drawbead and binder revision, and automated process iteration; (3). Demonstrated the technology on industrial stamping dies.	N/A - Enabling technology				Although tremendous progress has been made during and since the completion of the project, challenges remain in technology development and industrial deployment. Critical among them are (1). Springback compensation for Class A surface panels such as hoods, doors and decklids, especially for local surface distortion; (2). Springback compensation for line dies following draw; (3). The accuracy of springback prediction since it is directly fed for die compensation.
Improved Automotive Suspension Components Cast with B206 Alloy (AMD405)	Establish commercial viability of B206 alloy (preliminary evaluation conducted in AMD305) for lightweighting of suspension compoenents, by providing needed fundamental information on the alloy system and overcoming technical issues limiting the light weighting applications of this alloy.	Front Lower control arm	Al 356-T6 (4.9 Kg)	Al 206-T7 (1.0 kg)	20%	Further optimize 206 alloy chemical compositions, thermal solution treatment and aging parameters.
Ultra Large Castings for Lightweight Vehicle Structures (AMD406)	Capability to cast large thin wall, high integrity, highly integrated aluminum and magnesium cast components exceeding overall dimensions of 1 m x 1 m.	Pickup truck shotgun rail.	Stamped Steel assembly compared to Mg casting. Steel (11.8 kg)	Thixomolded Mg (7.0 kg)	Cast magnesium design achieved a 22% lower cost and 67% lower weight than the conventional multi-piece steel design.	Suppliers with large high pressure die casting machines. 5000 ton plus machines required for larger highly integrated components.

Die-Cast Net-Shaped Hole Process Development (AMD407)	Resolve highest priority technical challenges associated with application of thread-forming fasteners (TFFs) into die-cast, net-shaped holes in aluminum and magnesium alloys. Those challenges are casting variation and cast hole position, shape and size resulting from the thermal, mechanical and metallurgical effects of the die casting process. The effects of hole size, shape and position must be evaluated to understand impact to joint clamp loads.	N/A - Enabling technology				accurately and dynamically measuring joint clamp load in assembly processes that use TFF's
Die Face Engineering (AMD408)	Five technology gaps were addressed in this project to meet critical industry needs: (1). Numerical technology for springback prediction; (2). Material modeling for improved simulation accuracy; (3). Die surface compensation for springback; (4). Industrial experiments for validation of developed technology; and (5). Industrialization process for implementation.	N/A - Enabling technology				The project identified the following remaining challenges: (1). Minimize the deviation between morphed surface and target mesh; (2). Enhance the edge smoothness (G1 and C0) between surfaces; (3). Improve automatic morphing quality and reduce manual fixing time; (4). More accurate prediction of springback on large flat binder areas on drawn panels; (5). Better utilization of different material models more efficiently in different situations; (6). Speeding up of simulation with the newly-developed features; and (7). Validation of their applications in line die simulations.
NDE Inspection of Resistance Spot Welds in Automotive Structures Using an Ultrasonic Phased Array (AMD409)	Ability to replace current manual destructive testing of resistant spot welded sheet and structures in zinc coated and uncoated steel with fast, accurate, robust, ultransonic phased array Non-Destructive Evaluation (NDE) tools and methodologies	N/A - Enabling technology				Personnel training in use of state-of -the art equipment, ability to automate.
Powder Metal Performance Modeling of Automotive Components (AMD410)	No previous simulation capability to evaluate a PM design. PM processing knowledge applied to ferrous and aluminum alloys.	Only simulation. No prototype attempted.		3.8% for ferrous PM bearing cap of the same design.	3.8% for ferrous PM bearing cap	Ability to transfer knowledge from University database to part manufacturer database. Simplifying the simulation analysis procedure so the software could be handed over to the design engineers.
Feasibility of Thermally Drilling Automotive Alloy Sheet, Castings, and Hydroformed Shapes (AMD501)	Achieving clamp loads that exceed the strength of the bolt in thermally drilled holes for selected hole diameters and material thicknesses in various lightwieght material alloys of Al, Mg, and steel, comprised of several thicknesses and product forms and confirm and determine which alloys and product forms are the most thermally-drillable.	N/A - Enabling technology				Al alloys can be thermally drilled but require additional steps such as pilot holes or pre-heating to produce extrusions that result in acceptable clamp loads Mg alloys can be thermally drilled but requires further development that deliver acceptable clamp loads

High-Integrity Magnesium Automotive Components (AMD601)	Increase magnesium casting supply base and improve magnesium cast component integrity. Four existing aluminum casting processes optimized for casting magnesium alloys. The processes included; Low Pressure, T-Mag (tilt pour), Ablation and Squeeze Cast.	Suspension control arm	Steel (2.3 kg)	Mg (0.68 kg)	29%	Develop high strength Mg casting alloy
Development of High-Volume Warm Forming of Low-Cost Magnesium sheet (AMD602)	Developed the process parameters through simulation and forming experiments to optimize formability for Mg-sheet Demonstrated fully-integrated warm forming process for Mg-sheet (5-10 jpm)	N/A - Enabling technology				Gap: Mg-sheet price is still not competitive with steel/Al Gap: Mg-sheet supply base is not established for continuous casting
Magnesium Front-End Design and Development (MFEDD): Design and Feasibility Study (AMD603)	Design and integration of Mg sub-systems (as opposed to single component applications)	Cadillac CTS (unibody) front end structure - Paper study only	Steel at 99.5 kg	44.3 kg Paper study only	44.5% Paper study only	Cost panelty $5-6/kg saved per technical cost modeling; Joining and corrosion protection; validation of corrosion, durability and crashworthiness
	Design and integration of Mg sub-systems (as opposed to single component applications) for body on frame vehicle application. Technical cost modeling of full process from parts manufacturing through corrosion treatments, assembly and repair.	F-150 (body-on-frame) front end structure - Paper study only Paper study only	Steel plus Magnesium at 57.1 kg	14.2 kg Paper study only	24.9% Paper study only	Cost panelty $5-6/kg saved per technical cost modeling driven by material cost; Joining and corrosion protection at high volume; validation of corrosion, durability and crashworthiness/material cracking for magnesium
Magnesium Front-End Research and Development (MFERD) Enabling Technology Development (AMD604)	Mg alloys and manufacturing processes (casting, extrusion, sheet forming and joining) for building Mg sub-systems; materials models and database on Mg crashworthiness, fatigue, corrosion and NVH.	N/A - Enabling technology				Joining and corrosion protection; validation of durability and crashworthiness
In-Line Resistance Spot Welding Control and Evaluation System Assessment for Lightweight Materials (AMD605)	No economically reliable method exists today to inspect resistance spot welds at production rates.	N/A - Enabling technology				Due to inability to obtain supplier participation, the project was canceled before technical work was able to commence. However one technical need was identified for further development of infrared thermography technology.
Integrated Computational Materials for Engineering for Magnesium (AMD703)	Establish quantitative processing-structure-property relationships for extruded Mg, sheet Mg and Super Vacuum high pressure Die Cast (SVDC) Mg and integrate with Mfg simulation and constitutive models	N/A - Enabling technology				Mapping the local properties to performance CAE model. Currently zoning approach is adopted. In the future, the local properties will be mapped to performance model on element level.

Development of Steel Fastener Nano-Ceramic Coatings for Corrosion Protection of Magnesium Parts (AMD704)	Address galvanic corrosion issues when joining magnesium components with steel fasteners	N/A - Enabling technology				Complete multi-layer coating evaluation and develop high volume production process.
Nano-Engineered Cast Components Elevated Temperature Mechanical Property Testing and Cost Model Development (AMD705)	Investigation of nanoparticle reinforcement to increase elevated temperature performance of aluminum castings without negatively affecting ductility for applications requiring high levels of mechanical strength at high temperatures.	N/A - Enabling technology				Substantial basic research and development must be performed to establish an engineering science and technology base for a solid understanding of strengthening, deformation, creep, and fatigue mechanisms in the nanometer range. Cost of nano-particles remains high. Excessive variation in silicon carbide powder chemistry and crystallinity from different sources.
Magnesium Front-End Research and Development (MFERD) Technology Development and Demonstration - Phase II (AMD904)	Manufacturability of Mg alloy components (AM60 casting, AM30/AZ31 extrusion, and AZ31 sheet) and joining processes (friction stir linear lap welding) and laser-assisted self-pierce rivets (LSPR)	N/A - Enabling technology				Durability and corrosion performance of the demo structure to be validated; new alloys and improved manufacturing processes needed; Improved materials models and computational tools needed
Optimization of High-Volume Warm Forming for Lightweight Sheet Alloys (AMD905)	Demonstrated non-isothermal warm forming process which incompasses significantly lower cost structure for a door inner Attained craftsmanship levels in aluminum similar to steel Managed die heat-up during start-up and production	Door inner panel	Stamped steel 5.92 kg	Stamped Al 2.34 kg	39.50%	Gap: No established coupled thermo-mechanical simulation model for formability studies. Gap: Run-at-rate production cell has not been established to verify thermal simulation predictions.
Corrosion Inhibiting Electrocoat System for Body-in-White Assemblies (AMD1001)	The ability to assemble Mg-Al-steel components prior to corrosion coating application will eliminate off-line assemble processes and allow for integration of BIW into existing production lines while improving lifetime corrosion protection - At the end of this project, a corrosion protection system consisting of a cerium-based conversion coating (CeCC) or a zirconium-based pretreatment and a commercial E-coat layer have been successfully deposited on individual, bi-metallic, and tri-metallic couples that have performed well during corrosion testing and are compatible with vehicle assembly processes.	N/A - Enabling technology				The corrosion protection system has been demonstrated in test-panel scale. Scale up to magnesium front-end demo structure will be the next challenge.

Avanced Planning: Exploratory Evaluation and Formulation of Projects in Lighweight Material Technology and Processes (AMP999)	Formulate Lightweight Material project proposals based upon performing preliminary evaluation of technological concepts in materials, and/or processes which appear to have significant potential for increasing the use of lightweight materials in vehicles.	Varies by individual project				Remaining technology gaps will be assessed in the upcoming (2012) Roadmap being prepared by the DOE and USDRIVE Materials Tech Team.
Design and Product Optimization for Cast Light Metals (LMD110)	Design Optimization and weight reduction	Suspension control arm	Ductile Iron (7.3 kg)	Optimized Al (2.5 kg)	65%	Continued OEM implementation of aluminum chassis components

Project	**Technology Gap Addressed**	**Light-weighted Component**	**Original Material/Weight of component (lb or kg)**	**Weight Reduction Achieved (lbs or Kg)**	**Weight Reduction Achieved %**	**Challenging Still Remaining**
Lightweight Door Outer Panel - ASP 090		2002 Jeep Liberty Door			17.2%	
Lightweight Front-End Structure - ASP110		Ultra Light Steel Auto Body Front End Structure	60 kg	12 kg	20.0%	
Future Generation Passenger Compartment - ASP 240		Industry Standard Passenger Compartment	246.8 kg	77.5 kg	31%	
Lightweight Front Suspension Lower Control Arm - ASP 340		Front Lower Control Arm (Current OEM Aluminum Part)			0%*	
Lightweight Rear Chassis Structure - ASP 601		Current OEM Rear Chassis	25.8 kg	4.1 kg	15.8%	
* Substituted AHSS for Al at equivalent mass and a cost savings of 34%						

Project	Technology Gap Addressed	Challenging Still Remaining
Enhanced Forming Limit Curve Effect - ASP 040	Need to develop enhanced forming limit curves to take advantage of observed parts with strains substantially in excess of conventional as-received forming limit curves.	Need to provide a better analytical tool to determine forming limits. Some hypothesis suggest that the Instantaneous N-value might be a better predictor but additional research is required to validate.
Advanced High-Strength Steel Stamping Project - ASP 050	Need to develop product design and manufacturing process guidelines to address issues related to the enhanced properties of advanced high strength steels (AHSS).	This project has been continued into the new cooperative agreement and is part of the Auto Steel Partnership's 2012 project portfolio. As new higher strength steels have been developed to enable lightweighting and provide enhanced safety performance there is a need to continue to address the issues related to the enhanced properties of these AHSS in manufacturing and design.
Tube Hydroforming Materials and Lubricants - ASP 060	The forming limits for steel in tubular hydroforming are poorly understood. The effect of prior strain induced in the tube conversion and bending processes need to be addressed. In addition, the tests to evaluate tube quality do not properly address metal forming issues relevant to tubular hydroforming. More information is needed on the fundamental material attributes that control the hydroformability limits of steel.	There is potential to improve the manufacturability of tube hydroforming using advanced techniques such as hot gas forming. Additional research would potentially lead to increased use of lightweight hydroformed tube technology in automotive applications.

Joining Technologies -ASP-070	Joining data for advanced high strength steels is needed to enable the greater use of AHSS in automotive applications for lightweighting.	The Joining Knowledge Management ASP 370 project will provide better information for welding engineers to design effective joints with AHSS however continued work on joining is needed to fully enable the use of the newly developed AHSS for lightweight automotive use.
Non-Linear Stain Paths - ASP 061	Steel parts do not respond the same way as virgin materials due to the strain-hardening and bake-hardening of the material and non-uniform thickness distribution which results from forming. There exists a need to provide a comprehensive set of experimental data and associated predictive models for several AHSS under non-linear strain path deformations.	This project has been continued into the new cooperative agreement and is part of the Auto Steel Partnership's 2012 project portfolio. As new higher strength steels have been developed to enable lightweighting and provide enhanced safety performance there is a need to continue to address the issues related to the enhanced properties of these AHSS in manufacturing and design.
Sheet Steel Fatigue - ASP 160	As designers attempt to optimize steel bodies to minimize metal thicknesses and enable use of higher strength steels they need additional design data to support their design work. Fatigue properties data on newly created higher strength steels is needed to better predict performance of components that are subjected to cyclic loads in the design analysis phase.	Continued work on fatigue in fusion welded joints is needed to further advance the use of AHSS in chassis applications.
Strain Rate Characterization - ASP 190	It is important to determine the behavior of advanced high strength steels under impact conditions in order to use the correct material properties in crash simulations.	Continued work on improving the analytical tools to better predict the material properties of newly developed AHSS is needed.

Tailor-Welded Blank Applications and Manufacturing - ASP 210	Tailor-welded blanks have the potential to produce lower mass automotive components. Additional weight savings can be gained by using combinations of advanced high strength steels. There is a need to investigate the manufacturability and formability of these new AHSS in tailor-welded blank applications.	The Future Steel Vehicle project identified tailor-welded blank technology as a key enabler of lightweighting, however cost barriers continue to prevent the wide spread application of the technology.
Tribology - ASP 230	The increased use of higher strength steels in the manufacturing process is difficult on die wear and tooling life. There is a need to understand the process parameters associated with die wear, such as heat build-up and die scoring and dimensional stability caused by springback variation. AHSS grades may require different lubricants and/or die materials to minimize the friction and die wear.	The Tribology project has evolved into the Stamping Tooling Optimization (ASP 360) project in the current cooperative agreement and will be continued in the 2012 A/SP project portfolio. There is a need to continue this important work as newer, higher strength steels are developed to support their use in the manufacturing process.
Future Generation Passenger Compartment Validation - ASP 241	The objective of the Future Generation Passenger Compartment Validation project is to validate the findings of the ASP 240 project on a five-passenger, four-door sedan production vehicle. The project goal was to reduce passenger compartment mass by 25% at cost parity to the base design while meeting all the safety requirements.	Additional work was conducted under ASP projects; Development of a 3rd Generation Advanced High Strength Steel (ASP 280) and Mass Efficient Architecture for Roof Strength (ASP 270).

NSF Funding for the Development of a 3rd Generation Advanced High-Strength Steel - ASP 280	Need to develop a 3rd Generation AHSS that is higher in strength and more formable than currently available commercial grades of AHSS.	The need for higher strength more formable AHSS continue to be a priority as the fuel efficiency requirements double from current levels. These 3rd Generation AHSS will require continued development in the areas of forming limits, hydrogen susceptibility, and joining. This continued work is necessary to provide a cost effective, lightweighting option for automakers to meet the future fuel efficiency requirements.
Strategic Roadmap for Joining Next Generation Lightweight Applications of Steels - ASP 310	The full benefit of using AHSS cannot be achieved because of the technical limitations encountered when joining these materials together. The auto industry lacks a roadmap for joining new lightweight steels beyond traditional methods.	There is a continued need to develop advanced joining technologies for newly developed high strength steels. For instance, when traditional automotive BIW AHSS grades are Gas Metal Arc welded with traditional equipment, procedures and joint geometries the fatigue of the weld and heat affected zone is that of mild steel. This limits the benefits of AHSS and requires added weight to meet requirements. Research is needed to improve the welding process to address this reduction in properties.
Vehicle Structural System Benchmarking - ASP 330	There is a need to benchmark vehicle structural systems to identify best practices relative to mass performance in manufacturing technology, materials, and system architectures.	There is a continued need to investigate best in class relative to mass performance of vehicles.

Precision Flow Form Application Development - ASP 350	Precision flow forming offers the potential to produce round sheet metal products at reduced mass and cost. There is a need to investigate manufacturing processes that will enable this technology and replace cast iron components at a potential mass savings of 50%.	The ASP 350 project was halted in early 2011 when potential patent issues were identified. No further collaborative work is anticipated as a result.

Project	Technology Gap Addressed	Component benchmarked	Original Material/ weight of component (lb or kg)	Weight Reduction achieved (lbs or kg)	Weight reduction achieved (%)	Challenges still remaining
Multi-Materials Vehicle Program Overview (MMV701)	Need for an oversight committee in USAMP to coordinate development of large scale lightweighting projects being conducted under ACC, AMD, and A/S P, specifically the composite underbody (ACC), the magnesium front end design and development (AMD, and the future generation passenger compartment (A/S P). This coordination would entail ensuring that each project was based on the same baseline vehicle, and that all engineering performance metrics were being evaluated against a consistent set of performance benchmarks.	N/A - Enabling technology				None. This oversight committee was established for a specific set of projects, which have now been completed. Key engineering metrics defined for vehicle attributes
Multi-Material Vehicle CAD/CAE Support (MMV702)	Need for a common repository for all CAE data and for all baseline vehicle cost modeling. This prevented each individual project being monitored in MMV701 from having to pay for establishing and maintaining their own baseline data.	N/A - Enabling technology				None. Since the individual projects were completed, there is no need for additional baseline vehicle CAE data maintenance or for conducting any more cost modeling on the baseline vehicle. Data, CAD, CAE models are available from the archive until 2016.
Baseline Cost Models and Estimates for MMV Donor Vehicle (MMV703)	Need for common baseline cost model and cost assessment for the baaseline vehicle to support the individual projects being monitored in MMV701.	N/A - Enabling technology				None. However, further development and refinement of cost models for lightweight technologies and manufacturing would improve robustness of future assessments.
Multi-Material Metallurgical Bond Joining to Steel (MMV704)	Need for a robust process to achieve a true metallurgical bond between cast aluminum and steel, and between cast magnesium and steel to help enable improved multi-material structural development.	N/A - Enabling technology				Ability to achieve a true metallurgical bond between magnesium and steel was not established, so this challenge still remains. While there was some laboratory success in achieving a metallurgical bond between aluminum and steel, more work needs to be completed to determine if this can be accomplished in high volume production type processes that include metal moldes instead of sand. Also, additional work is required to identify appropriate production components for the technology.

Lightweight 7+ Passenger Vehcle (MMV903)	Need for analysis based determination of weight reduction targets required to enable a current production 7-passenger minivan and an 8-passenger CUV to achieve fuel economy improvements of 40-45% and 20-25% respectively, when retrofitted with smaller current production 4-cylinder engines and state of the art transmissions, while maintaining the ability to meet the driving performance metrics of the current production vehicles.	N/A - Enabling technology	Need to develop cost competitive design and manufacturing strategies for full vehicle weight reduction while meeting all vehicle performance, safety, durability, noise, vibration and harshness requirements plus vehicle dynamics attribute performance requirements.

Project	Technology Gap Addressed	Component benchmarked	Original Material/ weight of component (lb or kg)	Weight Reduction achieved (lbs or kg)	Weight reduction achieved (%)	Challenges still remaining
Non-Destructive Inspection of Adhesive Metal/Metal Bonds (NDE 601)	Non-destructively determine the strength of automotive structural adhesive joints.	Not applicable/enabling technology				Improve the understanding of the adhesive bond strength at the beginning of the adhesive bead.
Enhanced Resonance Inspection for Light Metal Castings (NDE 701)	A rapid, reliable and inexpensive non-destructive test to ensure the structural integrity of light metal castings.	Not applicable/enabling technology				Resonance inspection requires a large number of parts to empirically develop a sort module to distinguish acceptable from rejectable parts.
Reliability Tools for Resonance Inspection of Light Metal Castings (NDE 901)	Resonance inspection relies on large numbers of parts to empirically build a sort module to accept or reject inspected parts.	Not applicable/enabling technology				The expansion and refinement of the computer based flaw library.
Reliability Tools for Resonance Inspection of Light Metal Castings (NDE 901)	Resonance inspection is unable to identify the anomaly size, location or type in a rejected part.	Not applicable/enabling technology				Development of software tools to predict the probability-of- detection (POD) of resonance inspection to performance-critical casting flaws.
Shearographic Non-destructive Evaluation of Spot welds for Lightweighting the Vehicle (NDE 1002)	Non-destructive test for the non-contact full field evaluation of resistance spot welds.	Not applicable/enabling technology				Determine the actual weld nugget size using the hybrid method of shearography and finite element modeling.