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

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Objective

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

Project Approach

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

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

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

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

Summary of Previous Accomplishments

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

2006 Accomplishments

Since October 1, 2005 the following has been accomplished:

- Sub-Liquidus Casting Process Evaluation for Test Part
  – Test part design completed.
  – Test part tooling design completed and tool fabricated
  – First iteration of die cavity fabricated
  – Decision made to evaluate Mg in addition to Al with SLC process
  – Design of Experiments developed to streamline evaluation of SLC process
  – Fluidity casting trial underway

- Thixomolding Process Demonstration for production of Ford "Shotguns"
  – Completed construction of thixomold tool for Ford "shotgun"
  – Completed "hot-runner" system critical to demonstrate ultra-large thixocasting capability
  – Completed flow simulations necessary to complete the tool design and guide design of experiment
  – Complete analysis for process optimization
  – Produced shotgun samples of AZ91 and AM60 Mg alloys
  – Successfully demonstrated multi-drop hot-runner technology

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

Future Direction

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

Introduction

The rationale for ULCs

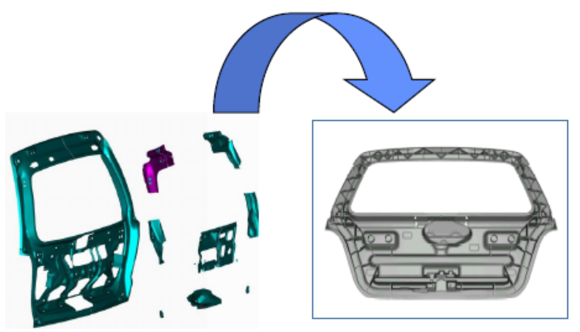

Figure 1

The majority of mass-market automobile and light-truck body structures are constructed of sheet-metal stampings fastened together with resistance spot welding. This method of construction tends to increase the weight of the body because it introduces structural redundancies. For example, an outer panel requires an inner panel for stiffness, which in turn might require local reinforcements. The casting process enables all of these structural elements and features to be integrated into a single piece, and thus has the potential to significantly reduce weight. This logic is illustrated with the example in Figure 1, which shows how a multi-piece stamped steel liftgate inner structure could be integrated into a single casting. There are numerous examples in the industry literature to be cited, however, the basic justification for ULCs is the ability to *reduce cost* by integrating components and *reduce weight* by taking advantage of the casting process to eliminate structural redundancies and, additionally, using lower-density material such as Mg and Al. Preliminary studies indicate large castings can be cost competitive with conventional stamped steel; however, a comprehensive, definitive case study comparing a true structural casting to conventional multi-piece stamped and welded construction has yet to be completed. Such a case study is essential for substantiating the rationale for ULCs and will be undertaken by the ULC Team.

Existing applications of large light-metal castings.

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

A notable example of a truly structural ULC is the current Ford F-150 radiator support structure (Figure 2). It is one-piece, thin-walled Mg casting that replaces seven major stamped steel parts for a 25 lbs. weight savings. It is integrated into the body structure where it contributes to torsional stiffness and plays a role in crash. If applications of structural ULCs like the F150 radiator support and other large quasi-structural parts already exist, why is there a need for an ULC project? These particular components are manufactured using the conventional high-pressure die casting (HPDC) process, which has some inherent limitations in achieving consistent mechanical properties.

Figure 2

Current manufacturing processes for producing large light metal castings.

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

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

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

Alternatives to HPDC

An attempt to demonstrate production feasibility of ultra-large, thin-wall, structural castings to achieve weight reduction at competitive costs resulted in a major effort by Alcoa and DOE[1] in the late 1990's. A novel, low-pressure, multiport hot-chamber injection process was pursued and technical difficulties arose relative to the metal-injector system. Alcoa regarded the ULC market to be futuristic and elected not to direct additional funds and resources to address the technical issues. At the end of this three-year effort by Alcoa and DOE, a number of minivan inner panels were cast for evaluation. A panel is shown in Figure 3. This is a single casting that replaces an assembly of 11 stampings. However, DOE, working with the AFS, continued to pursue ULCs. As a result, two documents[2,3] demonstrating the potential value of ULCs were produced. These studies showed that ultra-large components could be produced at costs competitive with steel structures for vehicles in the range of 70,000 units per year. At the higher volumes, traditional steel stampings become more cost attractive. The primary difference for the volume transition is the lower tooling costs associated with castings versus tooling required for stampings and subsequent assembly.

Figure 3

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

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

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

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

THT’s “SLC” process is a system that’s compatible for using multiple injectors. In addition, the process has been shown to produce castings in a T5 temper having properties approaching those requiring a full solution heat treatment (e.g., T6). It has long been concluded that thin-wall Al ULCs must be used in an “as-cast” condition or a T5 condition. The high costs due to dimensional management (i.e., straightening) associated with the solution heat treatment process must be avoided. Finally, small Mg automotive structural parts are now manufactured utilizing the Thixomolding process. Recently, hot-runner technology has been developed and demonstrated by Husky. The combination of larger available machines (e.g., 1000-ton and greater) coupled with hot runner technology makes the Thixomolding process a very attractive candidate for producing ULCs.

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

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

The SLC Process

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

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

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

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

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

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

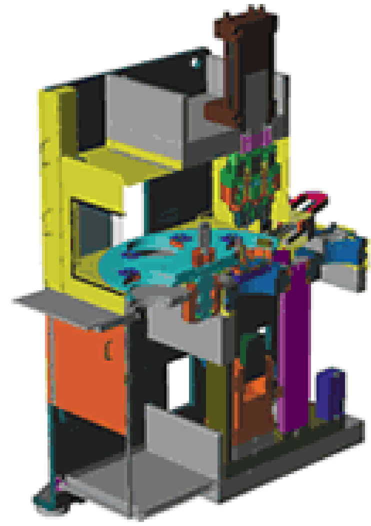

Figure 4. THT SLC casting machine.

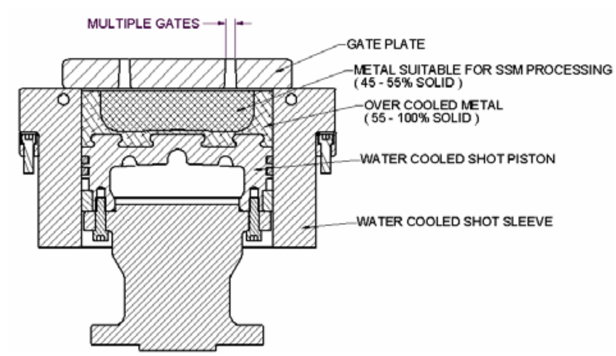

Figure 5. SLC shot sleeve.

The Thixomolding Process

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

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

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

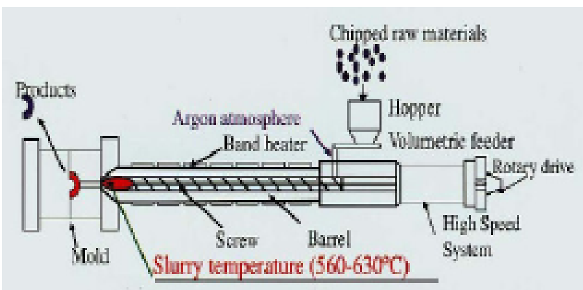

Figure 6. Thixomolding schematic.

Process Evaluation-"SLC"

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

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

Figure 7. Test part geometry.

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

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

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

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

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

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

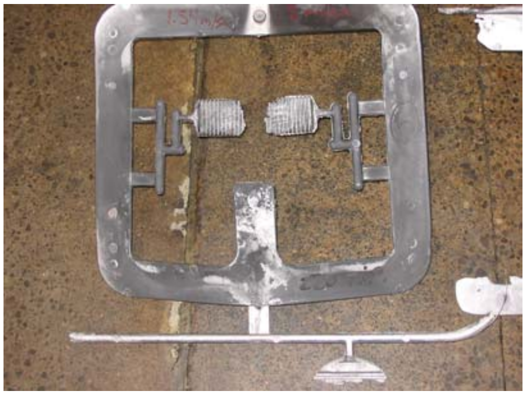

Figure 8. Fluidity test part 2.5-mm-thick A356.2.

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

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

"Real-World" Vehicle Application

It is important to demonstrate that the process knowledge gained can be applied to real-world vehicle lightweighting. The demonstration chosen by the ULC team is to replace the conventional multi-piece steel structure that forms the inner front fender—known in the industry as a “shotgun”-- with a single casting. The “shotgun” structurally joins the A-pillar to the radiator support structure on Ford light trucks. The simulation of the part filling at four drops via hot-runner technology is shown in Figure 9. Depicted in Figure 10 is the “shotgun” (42 inch length) for the passenger side with the attachment to the radiator support at the right and A-pillar attachment to the left. This was produced in AM60 Mg alloy.

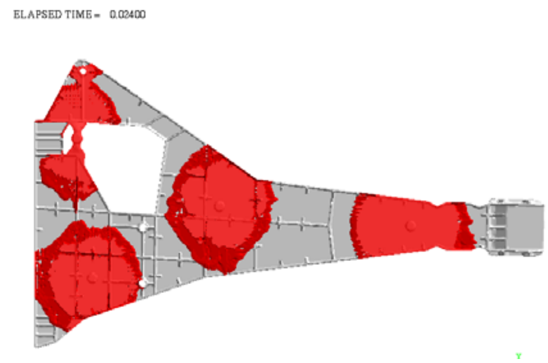

Figure 9. Snapshot of flow simulation and filling pattern for 4-drop hot runner.

Figure 10. Thixocast AM60 “shotgun.”

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

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

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

While this particular component would not necessarily be considered “ultra-large,” it embodies the geometric elements and manufacturing challenges that might be encountered in a much larger component, such as an entire bodyside. The shotgun application is of further interest to researchers because it is integrated into the body structure (Figure 11) where it contributes to stiffness (which has durability and NVH implications) and plays a role in conducting and absorbing crash energy (Figure 12).

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

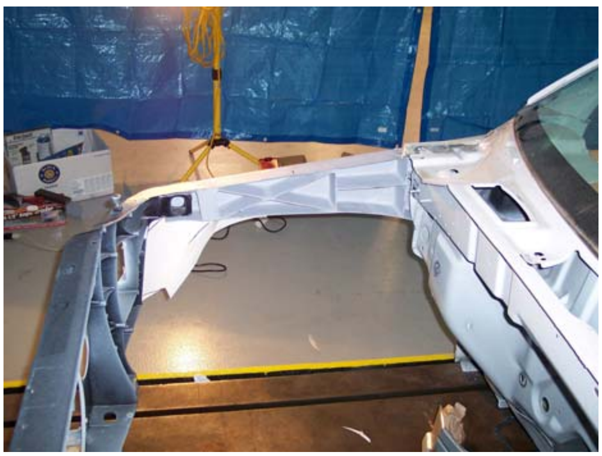

Figure 11. Shotgun will be integrated with the body structure.

Figure 12. Shotgun must manage crash energy.

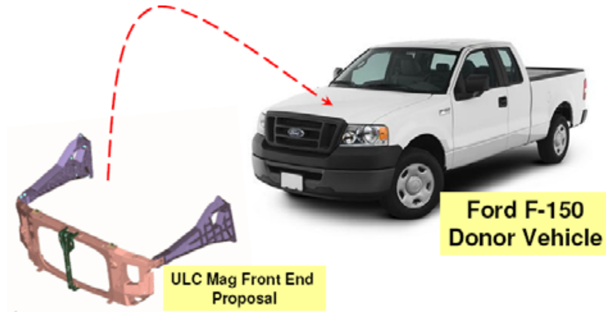

Figure 13. A demonstration front-end structure consisting entirely of large castings will replace conventional steel construction.

Conclusions

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

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

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

Presentations and Publications

No publications or presentations have been made at this time.

References

1. Final Report, Subcontract No. 86X-SU545C, "Development of a Casting Process for Ultra-Large Automotive Components," April 28, 2000.

2. AFS Project ORNL-ULC, July 16, 2002.

3. AFS Project ORNL-ULC-II, July 30, 2003.

4. "Sub Liquidus Casting (SLC): Process, Concept and Product," J. Jorstad, M. Thieman, R. Kamm, M. Loughman and T. Woehlke, 2003 AFS Transactions, No. 03-162.

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