I. Ultra-Large Castings of Aluminum and Magnesium

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Objective

Assess the manufacturing feasibility, economics and mass-reduction potential of thin-wall structural castings of aluminum and magnesium 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 to the American Foundry Society (Project ORNL-12401) which benchmarked various casting processes to assess their suitability for manufacturing 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. Pha*se II* is focused on designing, analyzing, producing and testing a "real-world" vehicle application that meets the ULC Team's ultra-large-casting criteria.
- 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 a more homogeneous distribution of properties while demonstrating consistent and predictable mechanical properties having improved strength and ductility.
- The major tasks for *Phase I* consist of part design, flow and solidification modeling, tool design/analysis/fabrication, correlation with casting trials, material characterization, process capability studies and an economic analysis.
- The main objective 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 FEAs for static, durability, noise-vibration-harshness (NVH) and crash analyses; system-level and full-vehicle prototype fabrication; durability testing; dynamic crash testing; and an economic analysis.

Accomplishments

Since October 1, 2004 the following has been accomplished:

- Selected THT Sub-Liquidus Casting (SLC) and Thixomolding for process capability evaluation. While SLC focus will be on aluminum, it is also possible to cast magnesium. Thixomolding is limited to magnesium.
- Industry participants selected. 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 their 1000-ton machine and necessary hot-runner technology.
- Ford conducted a preliminary cost study that indicates the economics of ultra-large cast structural parts are competitive with conventional stamped steel automotive structures.
- A "test part" has been designed that 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 implementation on a Ford vehicle program will be used to evaluate the capabilities of the Thixomolding process.
- Detailed statements of work have been 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 the test part is in progress under a subcontract to Promatek. Modeling has been subcontracted to EKK and Hitachi by G-Mag.
- Design geometry/solid modeling for the "real-world" part is nearing completion. Preliminary FEA studies for static crash, dynamic crash, and durability analyses have been completed by Ford.
- A newly developed manufacturing process, Ablation Casting, appears to be adaptable and scalable to potentially produce high-quality ULCs. A purchase order to Eck Industries has been issued to produce a “test part” geometry very similar to that pursued by MAGNA/Promatek. These parts are scheduled for production near the end of 2005 and will be evaluated by the ULC Team.

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 semi-solid die-casting processes. It may, however, become necessary to change direction and explore other manufacturing processes if insurmountable difficulties arise that inhibit attaining desired casting mechanical property levels or inhibit process scalability. Therefore, if other suitable processes are identified and appear to have potential, the ULC team will consult the AMD Board of Directors to request modifications to the project scope, timing and funding.

The Rationale for Ultra-Large Castings

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 ultra-large castings (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 magnesium or aluminum. 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.

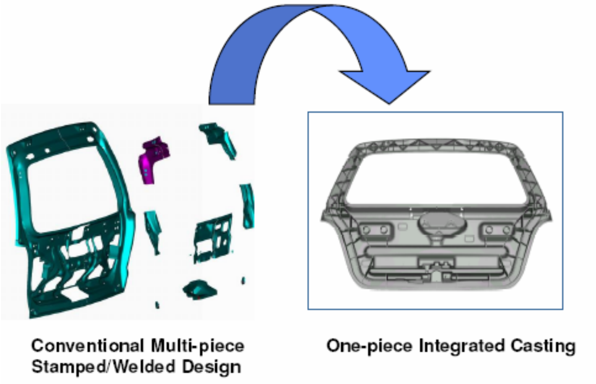

Figure 1. Single casting integrated from a multi-piece stamped steel liftgate inner structure.

Existing Applications of Large Light-Metal Castings

There are many examples in the industry of what are considered ultra-large castings such as die-cast magnesium 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 an ultra-large structural casting is the current Ford F-150 radiator support structure shown in Figure 2. It is a one-piece, thin-walled magnesium casting that replaces seven major stamped steel parts for a 25-pound weight saving. It is integrated into the body structure where it contributes to torsional stiffness and plays a role in crash.

Figure 2. An example of an ultra-large structural casting.

If applications of ultra-large structural castings like the F-150 radiator support and other large quasi-structural parts already exist, why is there a need for an Ultra Large Casting project? Because these particular components are manufactured using the conventional High-Pressure Die Casting (HPDC) process, which has some inherent limitations in achieving consistent mechanical properties.

Current Manufacturing Processes

The F-150 radiator support and most large quasi-structural automotive magnesium 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 of magnesium lack the level of ductility and other desirable mechanical properties for these structural applications. Therefore, further uses of magnesium HPDCs beyond today's applications are limited by the process capabilities and by the mechanical properties achievable with conventional die-casting. Although premium vacuum HPDC's of aluminum are utilized for large structural components, costs are not competitive with conventional steel assemblies. Modest properties are achieved with solution heat treatment and this requires a costly dimensional management process. Current premium aluminum structural HPDC parts are relatively expensive.

Utilizing a relatively simple process such as HPDC to make structural parts is highly desirable by the industry. Unfortunately, the presence of porosity in magnesium HPDCs has a detrimental effect on mechanical properties. A plethora of countermeasures have 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 ultra-large castings 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 magnesium die castings since magnesium is not able to be recycled in-process. As casting size increases, runner systems become larger and more complex, increasing tooling cost and necessitating the use of larger tonnage die-casting 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 but 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 1999 end of this three-year effort by Alcoa and DOE, a number of minivan inner panels were cast for evaluation; a panel is shown below 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.

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

Figure 3. A single casting that replaces an assembly of 11 stampings.

The efforts by AFS and DOE identified candidate processes suitable for ULC's 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 magnesium and aluminum alloy castings;
d) the THT Inc., sub-liquidus casting process, "SLC," to produce aluminum castings via a semi-solid process;
e) the Thixomolding process to form magnesium solids into quality cast components in a semi-solid process without having to handle molten magnesium.

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, d) and e), and these were selected for demonstration of ULC technology. THT's SLC process is a system that is compatible with the use of 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 aluminum 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 solution heat-treatment process must be avoided. Finally, small magnesium 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 T-5 heat treatment without losing ductility. This allows the castings to achieve required mechanical properties without the dangers of blistering, distortion or quench stresses associated with the full T-6 heat treatment required of other structural casting processes.

The SLC Process

The SLC process[4] 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 die-casting cycle. SLC is suitable for casting both aluminum and magnesium.

The SLC machines (See 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 (See Figure 5), 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

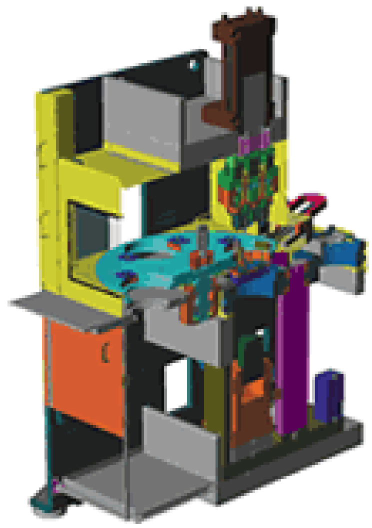

Figure 4. THT SLC casting machine.

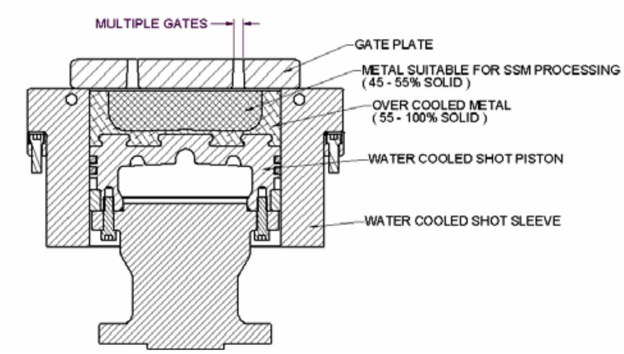

Figure 5. SLC shot sleeve.

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.

The indexing table feature 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 slot 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. When starting with normally grain-refined melt, the process provides globule sizes in the range of 75 microns. Mechanical properties achieved in castings from slurries are comparable to, and sometimes higher than, those realized from magnetohydrodynamics-stirred, billet-based SSM castings.

The Thixomolding Process

Another SSM casting variation is the Thixomolding process, which offers higher ductility magnesium castings with high strength and low wall thickness. Thixomolding combines conventional die-casting and plastic injection molding into a one-step process for the net-shape molding of magnesium alloys (See Figure 6).

The process requires no investment in molten-metal process and handling equipment and eliminates the safety hazards of handling molten magnesium. 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), magnesium alloy feedstock is thermally processed by the rotating screw. 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.

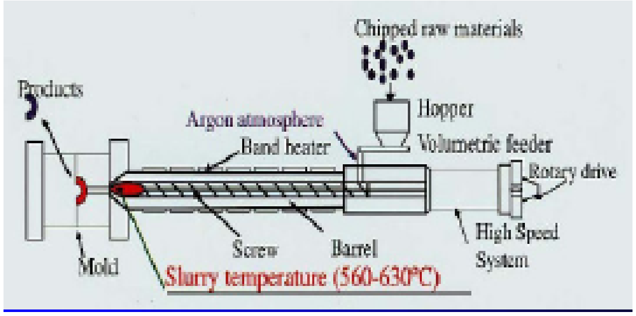

Figure 6. Thixomolding schematic.

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.

Process Evaluation

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 1, 2, 3 or 4 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 (25 mm) will be the first action step in Phase I. The flow path will follow the same outline as the test part. Following the fluidity trials, 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:

Figure 7. Test part geometry.

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 eight locations will be selected for tensile, yield, and elongation 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).

At this point, the test-part geometry will only be used to evaluate the SLC process using aluminum alloy. The same test part geometry could also be used to evaluate magnesium cast with the SLC process.

Evaluation of the Thixomolding process, which is much more mature than SLC, will focus directly on the "real world" vehicle cast part (Figure 8).

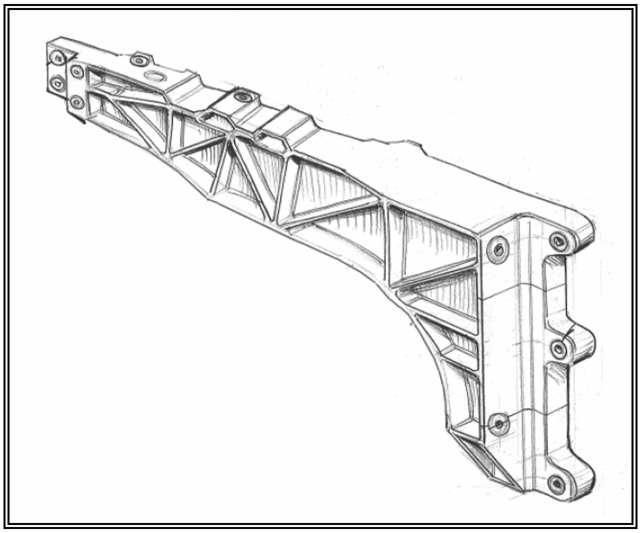

Figure 8. "Real World" application (shotgun).

Materials characterization will likely be based upon excised specimens from the cast vehicle parts.

“Real-World” Vehicle Application

It is important to demonstrate that the process knowledge gained can be applied to real-world vehicle light-weighting. 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 (See Figure 8).

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 body side. The shotgun application is of further interest to researchers because it is integrated (See Figure 9) into the body structure where it contributes to stiffness (which has durability and NVH implications) and plays a role in conducting and absorbing crash energy (See Figure 10).

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

Figure 9. Cast shotgun is integrated with the body structure.

Figure 10. Shotgun must manage crash energy.

Conclusions

The ULC Project has made good progress since its October 2004 kickoff. 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. The Thixomolding process has the potential to produce low-cost large magnesium castings with mechanical properties much better than those achievable with High Pressure Die Casting (the industry's preferred process). The SLC similarly offers the potential to produce aluminum ULC parts having properties and production costs not achievable by premium vacuum die-casting processes. 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 an OEM vehicle program. In fiscal year 2006, the team expects to continue to assess the capabilities of SLC and Thixomolding by analyzing parts produced by both processes.

Presentations and Publications

No publications or presentations have been made at this time.

References

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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.