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Alcoa Inc.

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Ultra Large Castings to Produce Low Cost Aluminum Vehicle Structures

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ABSTRACT

Through a cooperative effort with the U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT), Alcoa is developing a casting process to produce ultra large thin wall components. The casting process is a low pressure, metal mold, multiport injection vertical casting process. The specific system for demonstration of the process is located at Alcoa's Technology Center and will be capable of producing parts extending 3 M long, 1.7 M wide and 0.4 M high. For example, single castings of car floor pan frames or side wall aperture structures are candidates for this installation. This shall provide a major opportunity to reduce the cost of lightweight transportation vehicle structures by (a) reducing the components or part count and (b) reducing the cost of assembly. To develop and demonstrate the process, an inner panel of the Chrysler minivan liftgate will be first produced on this system. Through computer analyses, the cast inner panel design was developed to satisfy both structural performance and casting process requirements. Currently, this is an 11 part assembly of steel components. At the time of this abstract, the numerous system components are in various phases of fabrication and site preparation is fully underway, with system shakedown beginning in the second quarter of 1999. Successful demonstration of caster system operation is anticipated to occur during the third quarter and production of a high quality product during the fourth quarter.

Although the process is targeted toward reducing the cost of lightweight trucks, buses and autos, consideration is being given to application in the aircraft industry.

INTRODUCTION/BACKGROUND

The manufacturers of ground transportation vehicles (i.e., autos, sport utility vehicles/light trucks/vans, buses, and large trucks) have major efforts to reduce vehicle weight. Reducing the weight drives environmental emissions downward and fuel efficiency upwards. However, penetration of aluminum products into this market is significantly limited due to its relatively higher cost. But cost is the sum of (a) the basic material product cost (e.g., sheet, extrusion or cast product) and (b) the fabrication and assembly costs required (e.g., forming, joining, finishing operations). The Ultra Large Casting Project was conceived and proposed to the United States Department of Energy in an effort to reduce the overall cost of lightweight aluminum structures that are to be produced in high volume (e.g., 100,000 units/year). For an automobile, Figure 1 identifies some typical parts that are candidates for ultra large castings. For example, the floor pan frame structure is normally produced using a number of formed steel stampings which are assembled via resistance spot welding. By producing a component as a single ultra large casting, the costs of multiple stampings, multiple fixtures for subassemblies and the assembly process itself can be eliminated. In addition, the process must be capable of producing part wall thicknesses as low as 3 mm with elongation exceeding 10%. In addition, a yield strength target of 130 MPa was chosen. The successful development of such a casting capability will necessarily reduce the cost gap between conventional steel assemblies and lighter weight aluminum components.

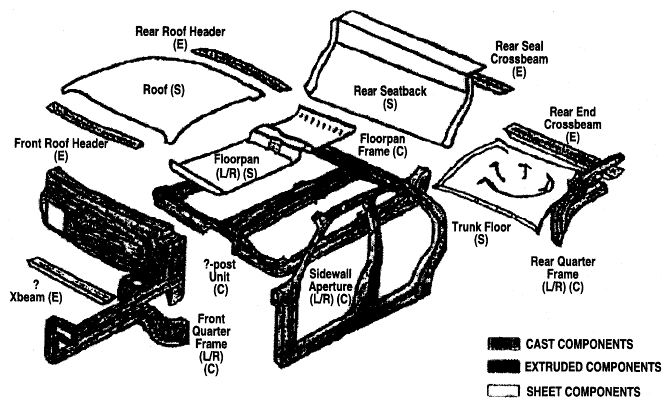

Figure 1. Candidate Parts for Ultra Large Castings

Although the payoff potential is enormous, the risk is high. As a consequence, DOE's Office of Heavy Vehicle Technologies is sharing the cost of this development with Alcoa Inc. Thus, the Ultra Large Casting Project was launched in June of 1996 with the project's completion scheduled for December 1999.

CASTING PROCESS APPOACH

The casting process to produce ultra large parts had been envisioned from the very beginning to consist of a vertical casting process employing multiport injection of molten metal. However, the multiple port injection was thought to be a modification of cold chamber die casting. At the initial stage of the project, an ideation process was conducted to examine various casting process routes that can result in (a) producing an inexpensive thin wall casting (e.g., thickness of 3 mm and greater) and (b) producing a casting of such a size and complexity to permit replacement of components that represent assemblies of multiple stampings. Three process routes were identified during the ideation session. The first was the original concept of a medium pressure, cold chamber, multiport vertical casting system. Due to the contemplated higher pressures (e.g., 1000 to 3000 psi) required, the cost of dies and caster press hardware is not expected to be sufficiently improved over the current AVDC (U.S. Patent 5,370,171, December 06, 1994, "Die Casting Process and Equipment," by J. R. Fields, et al., Alcoa) process currently producing the world's highest quality thin wall castings for the automotive market. The second process option was employment of the level pour process. The level pour casting process has been practiced by Alcoa in the aerospace market and applications continue to be explored today. Although the process promotes directional solidification, this process is not compatible with complex part geometries. Further, the attached runners used to feed the part are extensive and their removal from large thin wall parts could become a major cost issue. The third option identified is low pressure, hot chamber, multiport vertical casting. Low pressure offers the opportunity to minimize the cost of molds and casting press machinery. Further, hot chamber injection offers the opportunity to maximize the metal yield and thermal uniformity. In addition, the specific manner of injection permits the timing of the various ports to match desired process conditions for the specific part and further permits injection mass flow profiles matching part geometry characteristics. The opportunity for reduced cost and the capability to produce a high quality large thin wall casting make this process the clear choice for development.

Having reached this conclusion, a significant project effort was undertaken. To successfully demonstrate the value of this approach:

a. A **demonstration part** was selected that represented size, geometric complexity, and could be fully evaluated against a conventional transportation component.
b. A hot chamber **injection system** was developed that was compatible with economics and met the injection needs of the process.
c. The **part design** must meet the structural requirements and the casting process requirements for a quality casting. Further, this analysis is used to optimize location and number of metal injection ports and establish the initial injection conditions.
d. Establish the system for **delivering the molten** metal to the injector system.
e. **Specify, fabricate, install and debug the system** components (i.e., metal main and holding furnaces, caster press system, the molten metal injection system and the permanent mold system). The caster system will be capable of casting the largest car component conceivable (e.g., floor pan frame, side wall aperture structure).

DEMONSTRATION PRODUCT

The inner panel of a Daimler-Chrysler minivan liftgate (i.e., current model series) was selected to be the demonstration component. It is shown in Figure 2A as an assembly of eleven steel stampings. Figure 2B presents this component as a single piece aluminum casting. Through Finite Element Analysis (FEA) of specific loads affecting deflections, the current design was shown to satisfy Daimler-Chrysler's performance requirements. An initial project goal was to meet the load versus deflection requirements while achieving a 40% weight reduction over the current steel panel assembly. After the cast aluminum part was designed to meet structural and casting process requirements, the weight reduction fell closer to 25%. Since the geometric envelope of the liftgate was required to match that of the current steel assembly and the design was stiffness driven, achieving a target weight reduction of 40% was extremely difficult. A design specific to aluminum from the outset would likely result in a 40% weight reduction.

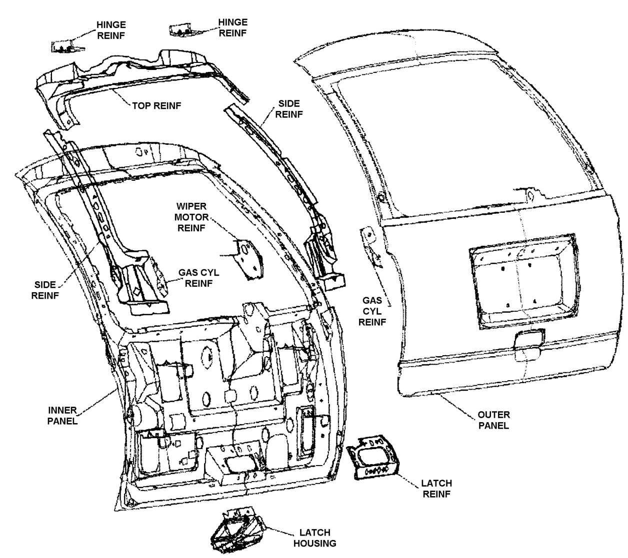

Figure 2a. Conventional Steel Inner Panel

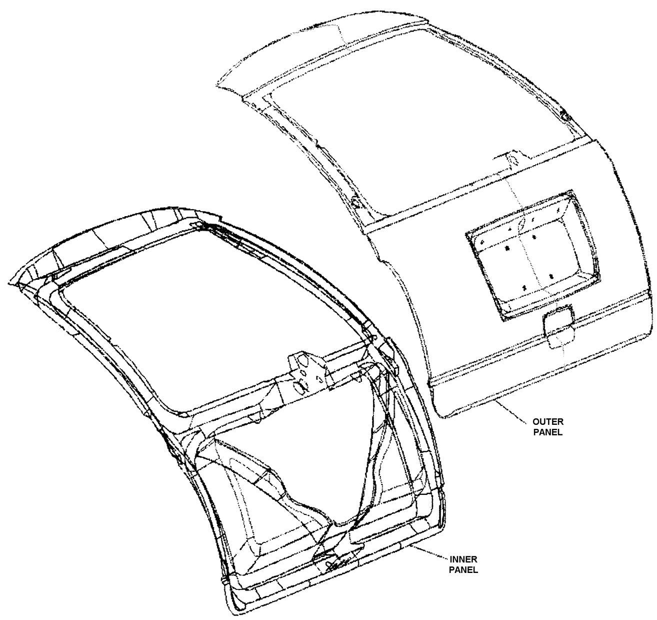

Figure 2b. Single Aluminum Cast Inner Panel

FILLING AND SOLIDIFICATION SIMULATION

Significant effort was required to simulate the filling and solidification of the casting. Alcoa's simulation capability has closely predicted actual results. Due to the unusually large part size, the time required to develop a mesh was much greater than anticipated. However, simplifications were used to quickly establish the individual filling schemes. Seven injection ports are included in the final arrangement. The filling analysis was used to avoid gas entrapment during filling, determine appropriate die temperature and temperature distribution, die heating/ cooling requirements, die coating thickness, avoid locations of shrink porosity or pores, proper location of chills and cooling requirements, establish proper velocity of metal during filling, and verify that the final design provides desired directional solidification. Some of the thermal data was utilized to assess die distortion and mechanical press impact upon minimizing distortion.

DIE DESIGN

After the design was verified to meet structural performance and casting process requirements, the permanent mold/die system could be designed in detail with fabrication to follow immediately. The die set was designed such that part ejection occurred from the upper die. An overview of the permanent mold design is shown in Figure 3.

The various major components are identified (i.e., holder frame, lower mold, upper mold, cover plate, spacer block, and top clamp plate. The mold cavity is oriented such that the inner (vehicle perspective) side of the inner panel is on the bottom. The sections running in the cross car directions above the window and below the latch are essentially located in the horizontal plane. Metal inlets/ ports are located in the lower cavity at seven points. Although the press is designed to accommodate dies for producing much larger parts, this particular die set weighs approximately 60,000 pounds.

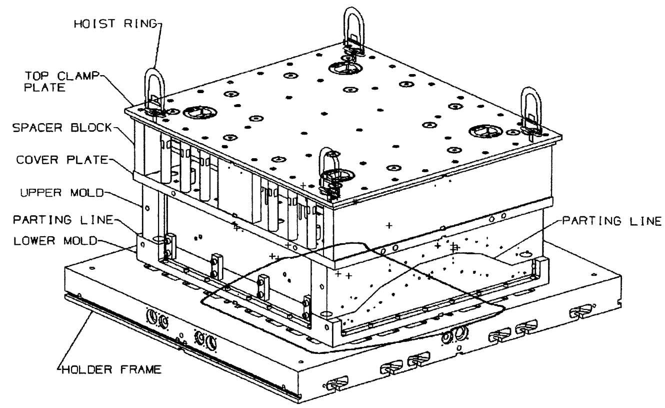

Figure 3. Liftgate Permanent Mold

INJECTION SYSTEM

This is the heart of the hot chamber casting process under development. A significant effort has been underway over the past 2 years to develop a system that is capable of delivering molten metal to the die cavity with:

1. Independent timing for each injection port of the die cavity
2. Fully controlled injection profile to match the part geometry requirements dictated by the filling analysis

The liftgate demonstration component will involve seven independently controlled molten metal injector units.

METAL DELIVERY SYSTEM

In addition to injecting metal into the mold cavity, metal conditions must be maintained and metal must be delivered to the injector locations. A unique metal delivery system consisting of a main melter furnace containing up to 30,000 pounds of metal and a holding furnace containing up to 2,500 pounds of metal located under the lower mold were developed. The design of the holding furnace allows for ready access of the seven injectors to molten metal. The combined operation of the two furnaces is expected to maintain quality metal under the die with minimal temperature variation (i.e., less than five degrees Celsius).

ULTRA LARGE CASTER SYSTEM

Much of the effort was directed to the product design and development of the injector system and the metal delivery system. To complete the casting system, it was necessary to include a press to operate the die, a system for removing and installing the die and an overall control system. The hydraulic press is sized to cast a part measuring 3 m by 1.7 m by 0.4 m. Due to a unique feature of the press, the depth can be increased significantly beyond the 0.4 m. The dry cycle time for the press is specified at less than 60 seconds. Overall casting cycles are anticipated in the two to three minute time range. The maximum tonnage for the press is 1100 tons. The actual process should require press clamping forces at only a fraction of this level. However, this is a development facility and additional capability provides greater process flexibility. For example, it may be necessary to apply a larger force to overcome minimal die distortion effected by thermal gradients just to fully close the die around the parting line. A view of the press with a Chrysler minivan placed between the upper and lower press platens (to scale) is shown in Figure 4.

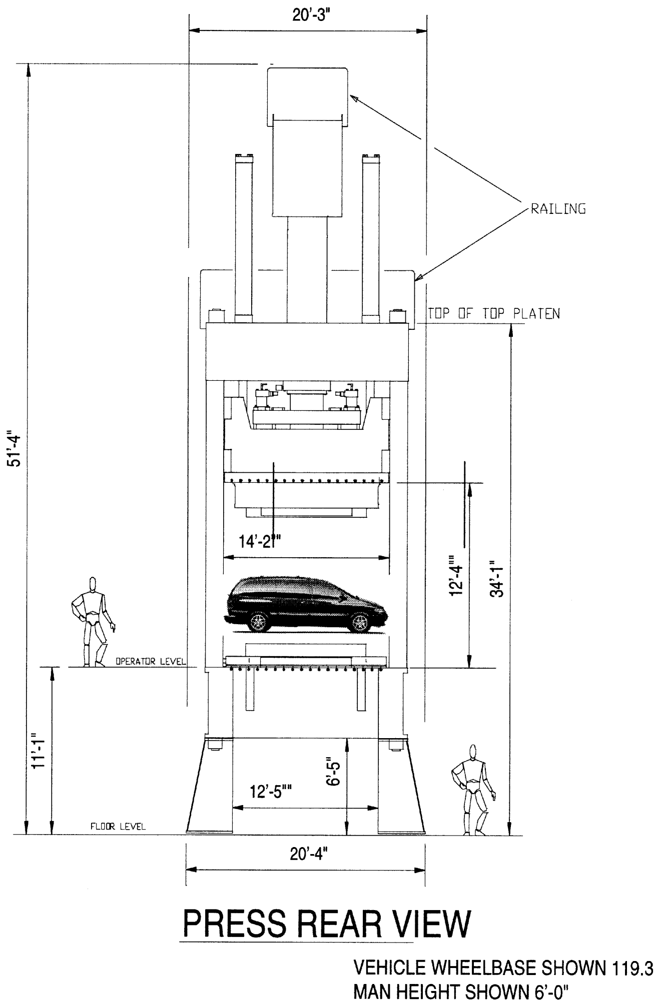

Figure 4. Minivan Located on Press Platen to Scale

PROJECT STATUS

At this time (April 19, 1999), much of the work is complete and some items are highlighted below for clarification:

a. raising of the high bay roof to accommodate the hydraulic press measuring 51' from the floor
b. redoing the building foundation to accommodate the caster system structure (e.g., 600,000 lbs) and lining floor area with refractory brick compatible with possible molten metal exposure
c. installing/erecting the press structure
d. fabrication and installation of the main furnace and the holding furnace together with required exhaust stack.
e. fabrication of the seven injector systems (i.e., gear reduction, motor, electrical drives, the actual hot chamber injector units) with spare components
f. fabrication of the die system (still in progress and scheduled to be shipped in mid-May).

The last major step is the installation of the electrical wiring and this work is scheduled to be complete during the first week of June.

Alcoa's Project Environmental Safety and Health Review Process has been initiated with some environmental, health and safety issues already identified. The main issues will be resolved prior to the anticipated June startup. Further, a detail plan is developed to identify key actions that need to be implemented to avoid unnecessary delays (e.g., ordering of metal, curing of the furnaces and having specific electrical power available for the refractory curing operation, and onsite preparation of the die set).

As subsystems become operable, shakedown will be conducted. When the furnace is cured and becomes operable, metal will be charged. Its performance to control temperature, chemistry and general metal quality will be determined. The injector units will be installed and tested in a dry cycle mode. The shakedown of the 1100 ton press has begun with main ram operation and operation of the three hydraulic pumps. The press shakedown shall continue through demonstration of maximum tonnage, demonstration of meeting operation cycle time specifications and satisfying all requirements listed in the acceptance test. In addition, extensive checks shall be required to determine that control and instrumentation meet the needs of the system.

The trials initiating metal injection into the die cavity is expected to begin in mid to late June. At this time, it is too difficult to predict the time required to resolve hardware/ software issues and achieve a sufficient level of process development to produce good parts. The project is to be complete following two demonstration production runs (i.e., 250 quality parts per run).

ULTRA LARGE CASTING PROCESS ECONOMICS

As stated at the outset, this effort is entirely directed toward reducing the cost gap between lightweight aluminum structures and current conventional steel structures. It is tempting to conduct a futuristic economic analysis considering a continually developing list of applications and corresponding business volume. Such an analysis would involve many assumptions far beyond that used in the following analysis. Since the minivan liftgate inner panel was chosen as the demonstration component, this is assumed to be the total business product. Since Daimler-Chrysler's vehicle volume approaches 700,000 units per year, this in itself represents a sizable business opportunity. Thus, a facility was developed that is capable of producing this entire volume of inner panels. A production facility layout used for the economics is shown in Figure 5.

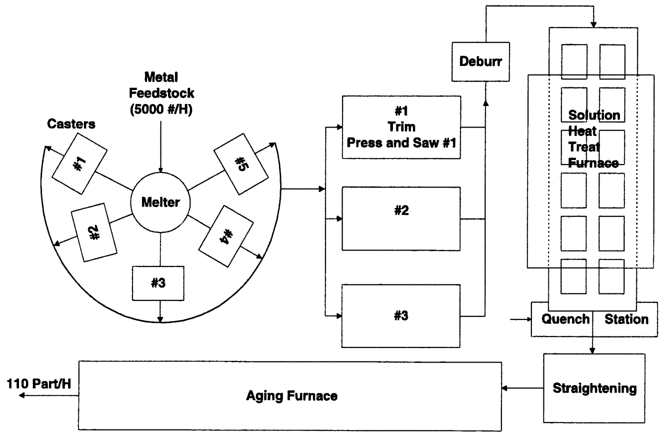

Figure 5. Production System Layout

The capital is comprised of:

a. Five caster machines
b. Metal injector system
c. Furnace and metal treatment equipment
d. Trim press and saw
e. Solution heat treat/air quench
f. Straightening press
g. aging furnace
h. and other items

In addition, allowances were made for die costs (i.e., initial purchase, repair and replacement costs) as well as repair and replacement for the injector system. An estimation of operating costs including energy (i.e., electricity and gas), labor, yield, scrap, uptime and cost of metal were developed. Obviously, much of the detail in this development can not be shared. However, we can share data shown in Figure 6 which indicates the fractions of costs associated with the major items less metal, overhead and profit allowances. The two major costs are labor and depreciation. In the final analysis, the results indicate that this 26 # cast aluminum part shall require a cost premium of $7.00 to $14.00 over the current steel part weighing 33 #. As noted earlier, the cast aluminum part was to be 40 % lighter. Due to the restricted working envelope of the existing part coupled with the stiffness driven performance requirements, the reduction was limited to the modest 25% used above. When weight reductions can reach the desired 40%, premium cost for lightweighting can fall below $1.00 per pound of weight saved.

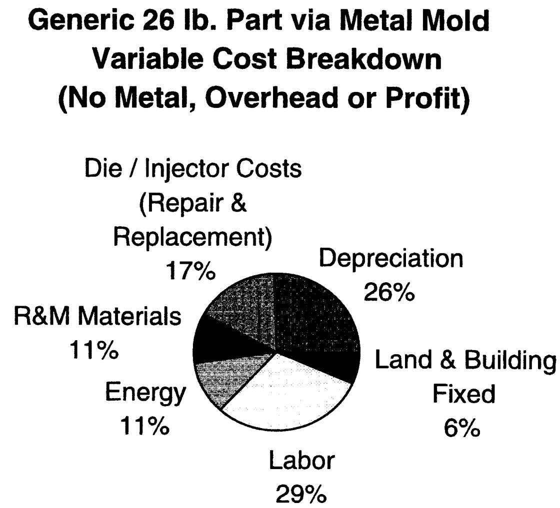

Figure 6. Cost Breakdown for Production Facility

CONCLUSIONS

This process route provides the opportunity to make a major cost reduction in lightweight aluminum vehicle structures. In fact, the cost of major aluminum components may very well approach the cost of assembled steel components (i.e., achieve a weight reduction without a cost premium). The success of this development depends upon two unique developments:

1. the hot chamber metal injection system
2. the maintenance of quality metal immediately beneath the mold for access by the injection system.

As this is a high volume process, this could provide a major advance in lightweighting of vehicles across the industry. However, technical challenges are great and problems will surely need to be solved before success can be declared.

ACKNOWLEDGEMENTS

During the course of this effort many people beyond the authors made significant contributions. These include the technical guidance by Dave Trudel on various aspects of the overall system and specifically the design of the die, James VanWert (AMCAST Industrial) formerly of Alcoa Inc. and Al LaCamera on the original concept of ultra large castings as a means to achieve major cost reduction, Jamal Righi for his continued support of the process development and specifically his direct involvement in the casting simulation work, Nicolas Bigler/Guy Arnaud/Dave Galinski of DBM for initial layout of the press and their contribution to the development of the injection system, Vince Perdeus for his support of the experimental process verification as well as development of the injector system, and Al Hummel, Douglas Robosky, Richard Slaugenhaupt, Karen Williams, Hank Guerke, Christine Retarides for their key specific roles in programming, designing, purchasing and installing the necessary equipment. The Daimler-Chrysler Liberty and Technical Affairs group provided assistance in selection of the demonstration part, part CAD files, part performance requirements and guidance on the casting design. The effective guidance provided by Dr. Sidney Diamond (DOE) and the Lockheed Martin Energy Systems project personnel at Oak Ridge National Laboratory has greatly facilitated the progress on this project. In a large project such as this, it's difficult to acknowledge all persons making an important contribution but this is an attempt and we apologize to those that are not mentioned.

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