

Advanced Lost Foam Casting Processes and Materials

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ABSTRACT

The lost foam casting process (LFCP) is a near-net shape casting process. This process is the most energy efficient casting process available. "Foundry Management and Technology" magazine analyzed the lost foam process and reported a 27% energy savings, a 46% improvement in labor productivity and 7% less material usage compared to other casting processes. The LFCP produces high value parts by combining multiple components into single castings, improving energy efficiency by achieving better metal yields, reducing materials consumption by eliminating cores, providing minimal post casting processing and improving as-cast dimensional accuracy. All of these process features reduce the total energy consumed during manufacturing.

Advanced lost foam casting processes (Pressure Assisted Solidification and Vacuum Assisted Mold Filling) have demonstrated the capability to improve mechanical properties, especially fatigue performance, for aluminum alloys and improve casting cleanliness, which reduces scrap, for ferrous alloys.

Advantages of LFCP that have not been fully utilized are 1) freedom from gray iron "skin" formation in ductile and compacted graphite iron and 2) elimination of hot tearing for high strength, cast aluminum alloys. These advantages, combined with the inherent near-net shape capability of the LFCP, would allow the economical production of lightweight, high strength and/or high stiffness automotive engine components, such as cylinder blocks and cylinder heads. These components would have a significant effect on vehicle fuel economy by allowing the production of diesel engines with lighter weight, greater performance and lower cost than currently possible.

INTRODUCTION

The lost foam casting process as we know it today was developed by M.C. Flemmings in 1964 but it didn't receive a lot of attention until 1982 when the Saturn Corporation made the decision to use this process to produce automotive cylinder blocks and cylinder heads. Cylinder blocks and cylinder heads are complex castings that are difficult to produce because of internal passageways that are difficult to mold. Also, getting the molding material out of these passageways is a challenge. The lost foam process is ideal for castings with complex internal passageways since the desired part is first produced as an assembly of foam slices; these slices can be "parted" such that intricate passageways are easily formed. Another advantage offered by the lost foam process was the possibility of integrating additional features into the casting that would normally require a separate casting plus assembly. Integrating additional features can significantly reduce cost due to the reduction of casting tooling, reduction of part inventory and reduction of assembly manpower [1]. Advanced lost foam casting processes, such as pressure assisted solidification and vacuum assisted mold filling, are currently used in limited production and have demonstrated the capability to improve mechanical properties. Mercury Marine annually produces 20,000 cylinder blocks for outboard marine engines using the pressure assisted solidification process. The application of 1 MPa (10 atm) of pressure during solidification reduces the size of the microporosity that is always present to some degree in aluminum castings [2-7]. By reducing the size of the microporosity, mechanical properties (particularly tensile ductility) are improved. Fatigue strength can be significantly improved if the remaining microporosity is so small that it is not a "critical" flaw. This allows the full potential of the material to be realized. Vacuum assisted filling is not

currently used in the production of lost foam aluminum castings but laboratory experiments have demonstrated that this process has the potential to eliminate certain defects, such as alligator skin, by assisting in the removal of foam pyrolysis products.

Current efforts are aimed at utilizing the lost foam process for complex military and advanced automotive components: high strength, lightweight, aluminum armor; high strength, high stiffness, compacted graphite iron cylinder blocks & heads and high strength, lightweight, aluminum cylinder blocks & heads. Compacted graphite iron is currently used for cylinder blocks in nineteen diesel engines produced by eleven manufacturers [8]. Compacted graphite iron is the material of choice for the new, high pressure, diesel engines since it is stronger and stiffer than gray iron and aluminum. The Audi, 4.2 liter, V8, TDI demonstrated that a properly designed compacted graphite iron engine can have a lower fully assembled weight compared to an aluminum engine of comparable size and performance [8]. Compacted graphite iron is also the material of choice for NASCAR and Pro Truck race engines since it maintains the ring seal longer due to lower bore distortion. However, compacted graphite iron has a tendency to form a deleterious gray iron skin when the highly reactive molten metal contacts a sand mold [9]. This skin is eliminated when compacted graphite iron is produced by the lost foam casting process since the molten metal contacts only a hydrocarbon foam and a refractory coating. High strength cast aluminum alloys, such as 201 or 206, are not used for engine applications since complex castings made from these alloys are prone to hot tearing during solidification. The lost foam process has considerably less mold “constraint”, which reduces the tendency for hot tearing. Also, aluminum alloys, like 201 and 206, have long solidification ranges, which tend to produce large amounts of microporosity throughout the casting. The benefits of solidification under pressure for complex shaped castings have yet to be quantified for high strength aluminum alloys.

EXPERIMENTAL METHODS

A combination vacuum/pressure vessel was constructed for laboratory experiments. This vessel is 4' in diameter and 6' tall, which provided sufficient working space to easily produce castings as large as a V6 cylinder block. The vessel can be evacuated or pressurized to 10 MPa (100 atm). The vessel was pressurized using a mixture of compressed laboratory air and nitrogen gas. Peak pressure was reached about 90 seconds after the pressurization was initiated. The vacuum/pressure vessel used for this study is shown in Figure 1.



Figure 1. Combination vacuum/pressure vessel for lost foam casting research.

A variety of crucible melting furnaces were used to produce the various aluminum alloys (A356, A319, A206) used in this study. Aluminum alloy A356 has a short freezing range and is often used for safety critical automotive parts (such as wheels and steering knuckles) due to its good strength and ductility. Aluminum alloy A319 has a short freezing range and is often used for cylinder blocks and cylinder heads due to its low cost and good machinability. Aluminum alloy A206 is difficult to produce since it has a long freezing range but it is often used where high strength is needed. For large castings, pre-alloyed aluminum alloy ingot was melted in a 225 kg stationary crucible furnace, Figure 2a. For small castings, pre-alloyed ingot or commercial pure aluminum plus aluminum master alloys were melted in pit-type crucible furnace using SiC crucibles, Figure 2b.



a) 225 kg (500 lb) stationary crucible furnace



b) pit-type crucible furnace

Figure 2. Crucible furnaces: a) 225 kg (500 lb) stationary crucible furnace and b) pit-type crucible furnace with a removable 27 kg (60 lb) capacity SiC crucible.

Degassing was performed with a rotary inert degassing unit using argon + 2% chlorine or nitrogen gas depending upon the alloy being produced. The degassing cycle was 6 minutes for the 225 kg (500 lb) crucible furnace, 4-6 minutes for a 27 kg (60 lb) crucible and 2-4 minutes for a 9 kg (20 lb) crucible. Grain refiners (Al-5%Ti-1%B) or structure modifiers (Al-10%Sr) were typically added near the end of the degas cycle to insure good mixing.

SOLIDIFICATION UNDER PRESSURE. One of the test castings studied was a wedge [4]. The wedge castings were filled through a sprue placed at the top of the pattern. A steel chill (2.5 cm x 4.5 cm x 25 cm) was placed at the bottom (thinnest section) of the wedge casting to promote directional solidification. A schematic of the wedge casting is shown in Figure 3.

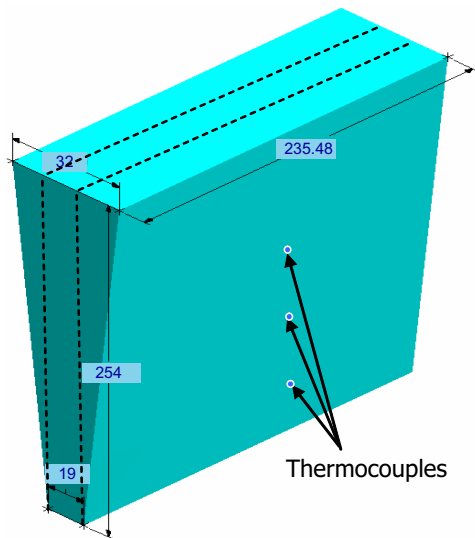


Figure 3. Schematic of the lost foam wedge casting (dimensions are in mm).

Application of pressure during solidification was achieved using the pressure vessel shown in Figure 1. A flask containing the coated foam pattern was placed in the pressure vessel. Molten metal was poured, the lid of the pressure vessel was closed and pressure was applied. A peak pressure of 1 MPa (10 atm) was applied until well after the casting had solidified.

A 19 mm thick plate was machined from the center of the wedge casting for further analysis. This plate was cut in half and one half was heat treated. The A356 alloy was given a T6 heat treatment: solution treat 540°C (1000°F) for 10 hours, quench in room temperature water and then artificially age at 160°C (320°F) for 5 hours. The A319 alloy was given a T7 heat treatment: solution treat at 490°C (920°F) for 5 hours, quench in water at 32°C (90°F) and then artificially age at 250°C (470°F) for 4 hours. The A206 alloy was given a T4 treatment: solution treat at 500°C (930 °F) for 2 hours, followed by 530°C (985°F) for 12 hours, quench in room temperature water and naturally age at room temperature for a minimum of seven days.

Blanks were sectioned from the heat treated plates at 2.5 cm (~ 1 in) increments from the thin section of the casting to represent different section thicknesses and cooling rates. Tensile specimens were machined from the blanks in accordance with the ASTM E8/B557 specification. Samples were 9.5 cm (3.75 in) long and 1.27 cm (0.5 in) in diameter (in the gage section) and with a gage length of 3.81 cm (1.5 in). Elastic modulus, tensile and yield strength were determined. Strain-to-failure was measured with a clip-on extensometer.

VACUUM ASSISTED FILLING. A cylinder head casting was used to determine the effect of vacuum assisted filling on casting defects. Two-on clusters of cylinder heads were poured from Mercalloy (9% silicon aluminum alloy) with and without vacuum assistance. After the sand was compacted around the casting cluster, plastic film was draped over the top of the flask and downsprue. A vacuum (0.07-0.09 MPa, 0.69-0.90 atm) was applied and a pouring cup placed over the downsprue and on top of the plastic film, thus sealing the flask. Pouring was then performed as usual. A wide range of pouring temperatures 698-766°C (1288-1411°F) was examined.

ADVANCED ALUMINUM ALLOYS. High strength aluminum-copper alloys, like 201, 206 and BAC 100™, have a long freezing range and are prone to hot tearing. To determine if the lost foam casting process could produce hot tear free, complex geometry castings from high strength (difficult to cast) aluminum alloys, a slotted plate casting was chosen. Castings were produced from BAC 100™, a new, microalloyed, high strength, aluminum-copper alloy [10].

COMPACTED GRAPHITE IRON. To determine if compacted graphite iron could be produced without a deleterious gray iron skin, castings were produced in the laboratory and at a production foundry. In the production foundry, four cylinder engine block castings were poured. The engine block castings were produced using a magnesium treated iron with the addition of ~0.12 wt% titanium. The engine block pour weight was 81 kgs (178 lbs). These castings were sectioned and thick section, thin section and near surface microstructures were closely examined.

RESULTS AND DISCUSSION

SOLIDIFICATION UNDER PRESSURE. Solidification under pressure had a significant effect on porosity and mechanical properties, particularly for aluminum alloys with a long freezing range. The only other method proven to reduce pore size is hot isostatic pressing, which is expensive and time consuming since parts must be shipped to an off-site location, processed and then shipped back. The effect of pressure on pore size is shown in Figure 4.