Accepted for Publication in Advanced Materials and Processes, 159(10), October 2001

Slurry-Based Semi-Solid Die Casting

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A new approach to semi-solid forming is described. The advantages of the new process are explained and commercial applications are discussed.

Abstract

A new process for the fabrication of high-quality, semi-solid-formed components offers advantages over components made via traditional semi-solid manufacturing methods: the need for specialty, added-cost raw material is eliminated; capital cost required for material handling is reduced; the issue of oxide formation on billets during reheating is avoided; and all forming scrap is recyclable in-house. Traditional semi-solid metal processing typically involves continuously casting metal bar stock with a special microstructure, inventorying and/or shipping this material, cutting the material to length, reheating the material to the semi-solid state, transporting the material to the forming press, and forming the component. The process described here eliminates many of these steps by producing a large quantity of semi-solid slurry from molten metal and maintaining a constant supply at the forming press. By reducing process complexity, eliminating capital equipment, and avoiding specialty raw material, this process provides the high-density, heat-treatable, pressure-tight components possible with semi-solid processing at reduced cost. The process, enabled by accurate temperature control and thorough mixing of the slurry, is fully integrated with existing vacuum die casting equipment and is currently used for the manufacture of automotive fuel rails.

Introduction

Semi-solid forming technology continues to make inroads in the manufacturing of mechanically demanding and pressure tight aluminum components because of its ability to provide near-net-shape components with properties far exceeding those of other casting technologies. Thus, semi-solid formed components have increasingly become a popular alternative for forgings, components machined completely from billet, and investment castings. However, in high volume applications – especially automotive – there is a constant pressure to reduce component cost. Conventional semi-solid forming, involving the use of heated billets, requires many processing steps and additional equipment not generally associated with die casting. This article describes Direct Slurry Forming (DSF), an alternative process for producing semi-solid feed material for forming that eliminates capital cost expenditures, reduces the number of steps required, and hence reduces the cost of semi-solid formed components.

Semi-solid metal behavior

At a very basic level, a “semi-solid” material is simply a mixture of a liquid and solid phase. In the context of semi-solid metal processing, a semi-solid is a mixture of rounded solid phase particles suspended in a liquid matrix. These metal mixtures are slurries, much like slush, ketchup, or sand castles – mixtures of dispersed solids within a liquid. In a metal alloy, thermodynamics determine at what temperatures a metal is solid, liquid, or partially solid and liquid. For most alloy compositions, there exists a freezing range between the states of solid and liquid where both liquid and solid exist together in the semi-solid state.

There are two basic ways of creating a semi-solid slurry for forming. The first, and most simple, is to begin with a liquid metal and cool it into the semi-solid state by applying shear forces (mechanical, electromagnetic, or otherwise) as the metal cools. These shear forces break up dendrites as they form during solidification and create rounded solid particles in the melt. This rounded structure is still apparent in the solidified metal and is the microstructural characteristic of semi-solid formed components. The second method for creating semi-solid feed stock is to take a solid piece of metal that has a globular microstructure (formed previously from the liquid state and allowed to solidify) and reheat it into the semi-solid state where the liquid matrix remelts. The two methods are illustrated in Figure 1 for a hypothetical binary aluminum alloy.

Conventional semi-solid processing of aluminum has followed the second path, which will be referred to here as the billet method; bars of stirred, continuously cast metal are subsequently cut into billets which can be reheated to the semi-solid state at a later time for forming. When the billets are reheated, they are transferred to the shot sleeve of a die casting press and forced under high pressure into a mold cavity. The process has the advantages of achieving high solid fractions (when formed into components, the billets are often at upwards of 50%-60% solid) and, assuming the bar stock is supplied by an outside vendor, allows the parts-maker to avoid the need to handle molten metal. The disadvantages of the process are that a premium must be paid for the bar stock, the bar must be cut to length depending on the part size, the billets must be re-heated from room temperature in what most times is a multi-station induction heating apparatus, and the heated billets must then be transferred either manually or robotically to the casting press. It is these additional steps and equipment that are eliminated by Direct Slurry Forming (DSF).

Process Description

Gibbs Die Casting Corp., a major automotive aluminum die caster, desired a process that could provide the advantages of semi-solid processed components, but at reduced costs much closer to those of die casting. Additionally, given the high volume nature of automotive business, process throughput was identified as being very important. A third requirement was compatibility with existing die casting equipment. To meet these needs, it was decided that the process must be capable of at least a 550 kg/hr (1200 lb/hr). production rate and that it accommodate the vacuum ladling process Gibbs uses for its die casting operations.

The process that was developed in response to these requirements can be separated into three steps: formation of semi-solid metal, maintenance of the slurry suspension, and transport of the semi-solid mixture to the die casting machine. Die casting operations typically have furnaces for melting ingot, and the molten metal is transported to holding furnaces at the casting press. This metal can be as hot as 650 ºC (1200°F) at the holding furnaces. Producing 550 kg/hr of partially solidified slurry is a matter of thermodynamics; incoming molten metal must be cooled and stirred sufficiently fast to remove enough heat to lower the temperature to the desired slurry temperature – typically about 600ºC (1112°F).

Two factors heavily influenced the design of the slurry furnace – the required heat removal rate and the need to maintain a near-constant temperature of the bath. Based on the production rates and temperature differences, it was found that about 20 kW of heat extraction were needed in the most extreme case. Additionally, it was necessary that with an average of 90 kg (200 lb) of molten aluminum addition every 10 minutes the bath temperature not vary more than ±1°C (±2°F). Each of these requirements dictated a furnace with large volume and high surface area. A cylindrical furnace 1 meter in diameter and 1 meter tall could contain 2000 lbs of slurry and remove 7 kW/m^2. With a temperature difference of 50°C (90°F) between liquid and slurry, specific heat of 60 kJ/kg for liquid aluminum, and latent heat removal of 77 kJ/kg, this configuration could meet the design needs.

The second step of the process is maintaining the slurry in a homogeneous, isothermal state as it awaits forming. In addition to the thermal requirements for creating a slurry discussed above, it is necessary to provide adequate shearing forces to the mixture to create the rounded solid particles and prevent agglomeration of the solids. In the arrangement described here, where heat is removed through the walls of the furnace, aluminum alloy would typically form dendrites at the outer walls of the furnace that would grow inward as solidification progresses. If the average temperature of the bath were maintained constant, the result would be completely segregated: a solid shell of low-alloy aluminum surrounding a high-alloy liquid center. However, the desired result is a uniform mixture of fine-grained solid particles in a liquid matrix. This result can be achieved by regularly scraping the walls of the furnace during solidification, breaking growing dendrites from the wall and moving them into the bulk of the bath. With sufficient shearing action, these dendritic structures are moved through the melt and coarsened into rounded structures by the flow of liquid around them. Figure 2 illustrates the viscous consistency of the resulting slurry.

Equally important to creating the solid portion of the slurry is keeping it uniformly distributed within the mixture. Because of density differences between solid and liquid phases, the solid particles in aluminum alloy A356 (a low-iron, aluminum-silicon casting alloy not typical in die-casting) will settle downward over time, resulting in a high concentration of solid particles at the bottom of a furnace, and very few of them at the top. To overcome this, it was necessary to introduce a method of agitation along a third axis. This was accomplished through the use of an impellor with inclined rotating blades that forced the flow of material upward in the melt. The final mixing system in the furnace consisted of an anchor-shaped rotor with vertical shearing rods located proximal to the furnace walls for the scraping of solidifying material, and an auger located within the anchor shape to promote vertical homogeneity. Figure 3 depicts the furnace and mixing configuration. This original mixing arrangement is the main difference between DSF and the original implementations of rheocasting, and it is what enabled for the first time commercial production of semi-solid aluminum components from slurry without billets. A more detailed depiction of this arrangement can be found in US Patents 5,881,796 and 5,887,640.

The final step of the process is transferring the slurry from the furnace to the casting machine shot sleeve. As mentioned earlier, it was desired that the existing vacuum ladling method be used as the transfer mechanism. This mechanism consists of vacuum drawing liquid aluminum through a tube into the shot sleeve of a cold chamber die casting press. Figure 3 shows the transfer tube, which is connected to a cold chamber shot sleeve. With liquid aluminum, because it has significant superheat, the metal flows through a tube without freezing, and when the vacuum is removed, the metal quickly flows back to the bath. A semi-solid slurry contains no superheat, and because it is partially solidified, it is prone to freezing. Another concern is the increased viscosity of the slurry, and whether the thickness of the slurry will prevent its flow through a tube. Therefore, the flow of slurry through a tube was modeled. Given a viscosity of 0.2 Pa.s for a slurry of 30% solid, it was predicted that not only would the slurry flow through the tube under vacuum, but the ladle time for 10 lbs (a typical shot weight) of slurry would increase by less than 10% over liquid aluminum. Actual practice closely matched the predicted results. It was also found that temperature control of the ladle tube is important to prevent freezing of the slurry. The tube must be kept at or above the liquidus temperature of the alloy. The ability to use the vacuum ladling technology was key to the success of this process because it eliminates the need to have a person or robot dedicated to the transfer of slurry from furnace to casting press.

Comparison with Die Casting

The DSF technique shares many similarities with conventional die-casting operations. The same presses and raw material can be used for DSF and conventional die-casting; therefore, no significant modifications need to be made to existing die-casting equipment when implementing DSF. Die materials are the same, and DSF achieves the same dimensional tolerances found in die castings.

In contrast, the resulting product has significant differences. Components manufactured by DSF are consistently leak-proof, even for difficult components that cannot be made reliably by conventional die-casting methods. Because of reduced porosity, mechanical properties of DSF products are superior to their die-cast equivalent. High temperature heat treatments, such as T6 heat treatment, are possible with DSF because of reduced gas entrapment in semi-solid castings. Finally, low-iron aluminum alloys not normally considered suitable for die casting because of soldering and die wear, including A356 and 357, can be formed via DSF because of lower temperature and latent heat.

Comparison with Billet Methods

The DSF process has a number of advantages over conventional semi-solid forming techniques, some of which are outlined below:

- Less energy is required during processing because metal is heated only once. There is no reheating necessary, as the semi-solid is formed only one time.
- Complexity is reduced because no multi-station heating systems are needed nor any manual or robotic handling of heated billets.
- Flexibility is increased because alloy modifications can be made in-house and solid fraction can be tailored to the application.
- Metal supply is less restricted because there is no need for the special semi-solid processed feed bar available only from a few suppliers.
- Capital cost is reduced because no sawing equipment, special induction heating systems, or robotic handling is necessary.
- Scrap cost is reduced because scrap can be recycled in house simply through remelting, and it does not have to be sold and converted back to billet stock.

Each of these differences contributes to a process that can provide semi-solid components at reduced cost.

Industrial Implementation

The DSF process has been in production at Gibbs Die Casting for over 18 months. The process currently manufactures automotive fuel rails (shown in Figure 4) that can be found on the Zetec engines of Ford Focus automobiles. Many other parts have been prototyped, including compressors, compressor heads, motor mounts, pistons, and clutch covers. The parts vary from thin-walled to thick-walled, pressure-tight to mechanically demanding, and single to multi-cavity. Figure 5 shows a variety of parts sampled with this process. The process lends itself well to high volume automotive applications where leak tightness is required, where improved mechanical properties are required over die castings, or where reduced cost is desired compared to other processes such as forgings or welded assemblies. The near-net-shape capabilities of semi-solid forming combined with DSF offer an exciting new cost competitive manufacturing solution.

For more information:

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Figure 1: Hypothetical phase diagram for binary aluminum alloy system

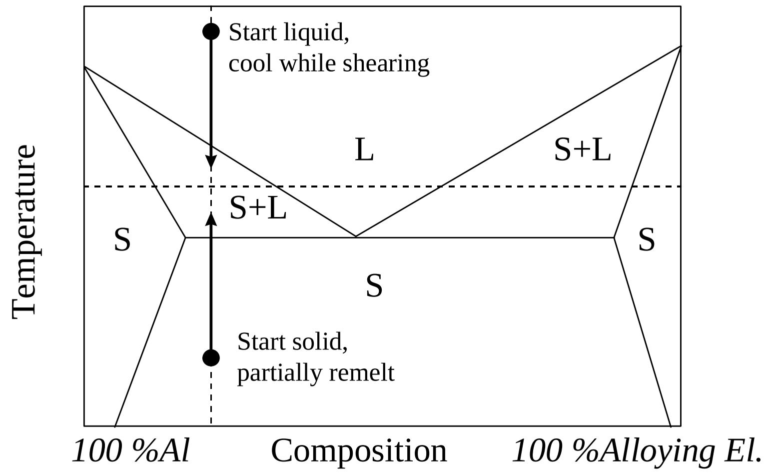

Figure 2: Sample of aluminum semi-solid slurry

Figure 3: Schematic of slurry machine components

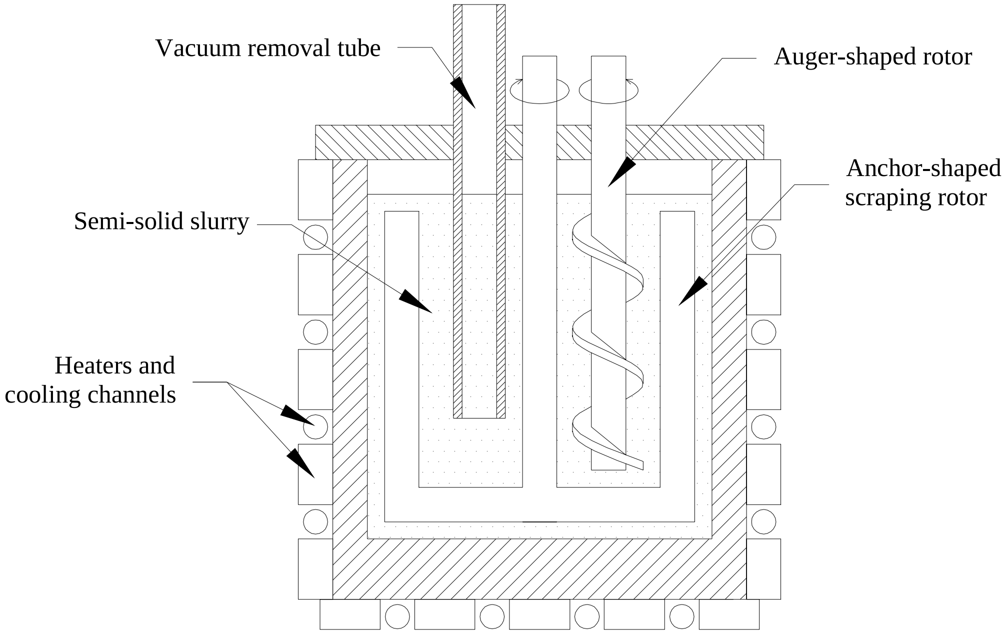

Figure 4: Automotive fuel rail manufactured by DSF

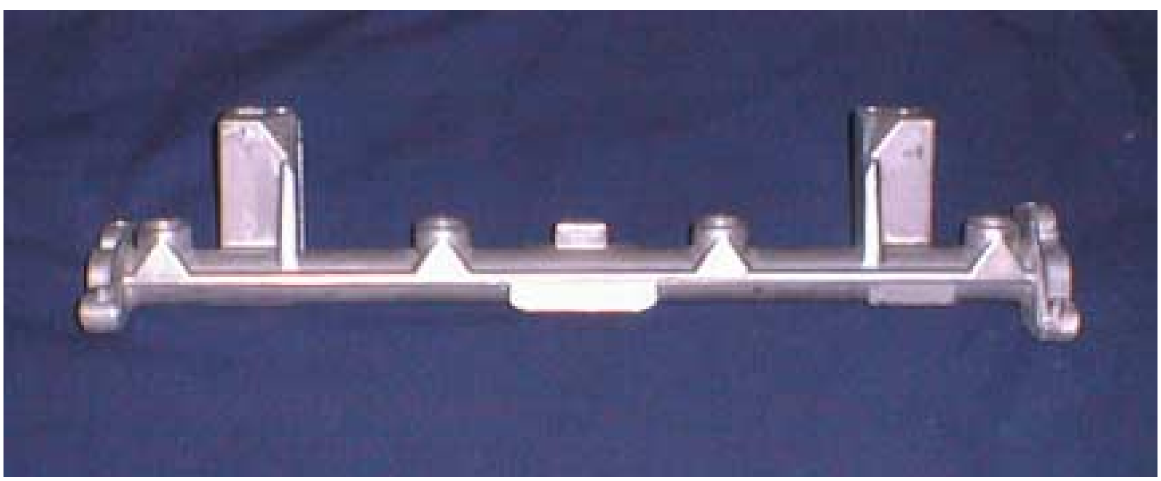

Figure 5: A variety of parts sampled or prototyped with DSF