Slurry-Based Semi-Solid DIE CASTING

A new process for the fabrication of high-quality, semi-solid-formed components offers advantages over components made via traditional semi-solid manufacturing methods.

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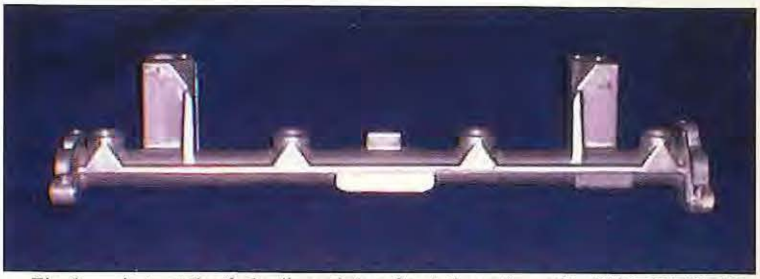

Fig. 1 — Automotive fuel rails are being direct slurry formed by Gibbs Die Casting Corp. The process is compatible with existing equipment, reduces costs, and provides high quality, pressure-tight components.

Direct slurry forming (DSF) is a semi-solid forming process that eliminates capital cost expenditures, reduces the number of steps required, and hence reduces the cost of semi-solid formed components relative to other semi-solid forming processes. Semi-solid forming continues to make inroads in the manufacture 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. For these reasons, semi-solid formed components have increasingly become a preferred alternative for forgings, components machined completely from billet, and investment castings.

Traditional semi-solid metal processing typically involves continuously casting metal bar stock with a special microstructure, storing and/or shipping this material, cutting it to length, reheating to the semi-solid state, transporting to the forming press, and forming the product.

The DSF process eliminates many of these steps by producing a large quantity of semi-solid slurry from molten metal, and by maintaining a constant supply at the forming press. Process complexity is reduced, capital equipment is eliminated, and specialty raw material is avoided. DSF provides the high-density, heat-treatable, pressure-tight components possible with traditional semi-solid processing, but at lower 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 in service for the manufacture of automotive fuel rails (Fig. 1).

This article describes the behavior of semi-solid metals, details the process steps, and compares it with die casting and conventional semi-solid processes.

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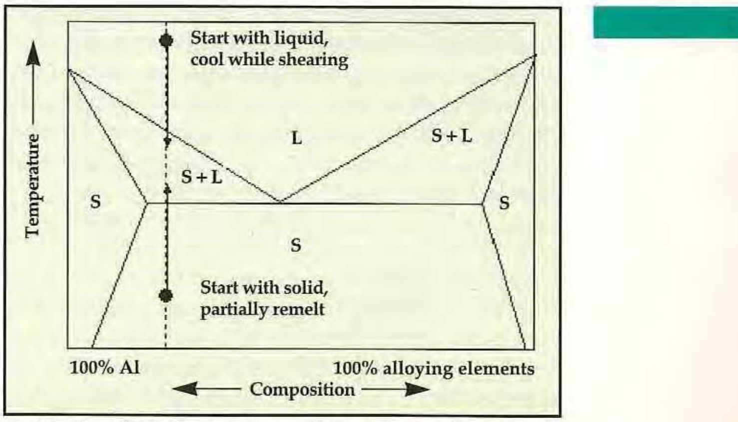

Fig. 2 — This diagram shows the two approaches to semi-solid forming. One is to begin with a liquid metal and cool it to the semi-solid state while applying shear forces. The other is to take billet with a globular microstructure and reheat it to the semi-solid state.

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, a freezing range exists between the states of solid and liquid where both liquid and solid persevere together in the semi-solid state.

Semi-solid slurries may be created in two ways. The simplest 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

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.

formed components. The second method 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 Fig. 2 for a hypothetical binary aluminum alloy.

Conventional semi-solid processing of aluminum has followed the second path, which will be designated 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 advantage of the billet process is that it achieves high solid fractions: when formed into components, the billets are often at upwards of 50% to 60% solid. Assuming that the bar stock is supplied by an outside vendor, it allows the parts maker to avoid handling molten metal.

The disadvantages 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 reheated from room temperature in what most often 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.

Process description

Gibbs Die Casting Corp., a major automotive aluminum die caster, needed a process that could provide the advantages of semi-solid processed components, but at a cost much closer to that of die casting. Additionally, given the high volume of the 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. It also had to accommodate the Gibbs vacuum ladling process.

The process 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°C (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 required slurry temperature – typically about 600°C (1100°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

Fig. 3 — The semi-solid state is a mixture of rounded solid-phase particles in a liquid matrix.

of heat extraction were needed in the most extreme case. Additionally, because an average of 90 kg (200 lb) of molten aluminum is added every ten minutes, the bath temperature may 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 one meter in diameter and one meter tall could contain 2000 lb 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, and these dendrites would grow inward as solidification progressed. If the average temperature of the bath were maintained constant, the result would be complete segregation: a solid shell of low-alloy aluminum surrounding a high-alloy liquid center.

However, the goal 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 3 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 con-

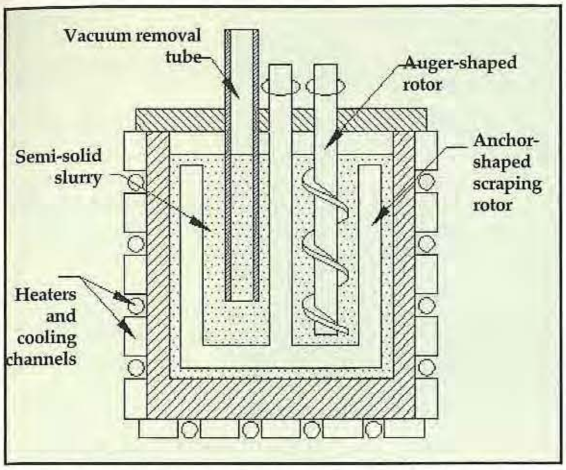

Fig. 4 — This diagram shows the design of the slurry forming furnace. The impeller has inclined rotating blades that force the flow of material upward in the melt. The scraping rotor shears growing dendrites off the walls and into the melt.

Fig. 5 — These are a sampling of parts made by direct slurry forming. The parts vasry from thin-walled to thick-walled, pressure-tight to mechanically demanding.

centration 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.

The answer was to agitate the melt by means of an impeller with inclined rotating blades that forced the flow of material upward in the melt. The final mixing system in the furnace consists 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 4 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 U.S. Patents 5,881,796 and 5,887,640.

The final step of the process is to transfer the slurry from the furnace to the casting machine shot sleeve. As mentioned earlier, the objective was for the existing vacuum ladling method to become the transfer mechanism. This mechanism consists of a vacuum that draws liquid aluminum through a tube into the shot sleeve of a cold chamber die casting press. Figure 4 shows the transfer tube, which is connected to a cold chamber shot sleeve. Because liquid aluminum has significant superheat, the metal flows through the tube without freezing, and when the vacuum is removed, the metal quickly flows back to the bath.

However, a semi-solid slurry contains no superheat, and because it is partially solidified, it is likely to freeze. Another concern is the increased viscosity of the slurry, because 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 Pascal-seconds for a slurry of 30% solid, it was predicted that not only would the slurry flow through the tube under vacuum, but also the ladle time for 10 lb (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. 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 are suitable for DSF and conventional die-casting; therefore, no significant modifications must 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. No reheating is necessary, as the semi-solid is formed only one time.
- Complexity is reduced because no multi-station heating systems are needed, and no heated billets must be handled.
- Flexibility is increased because alloy modifica-

Capital cost is reduced because no sawing equipment, special induction heating systems, or robotic handling is necessary.

tions can be made in-house, and the solid fraction can be tailored to the application.

• Metal supply is less restricted because it is not necessary to cast only the special semi-solid processed feed bar available from only 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. Automotive fuel rails that can be found on the Zetec engines (Fig. 6) of Ford Focus automobiles are slurry cast. 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.

DSF lends itself well to high-volume automotive applications where leak tightness is required, where

Fig. 6 — The Ford Zetec SE 13 DISI engine is a prototype 1.1 liter, 3-cylimder, direct fuel injection engine designed for reducing emissions and improving fuel economy in congested urban environments. Fuel rails on the Zetec engines for the Ford Focus are slurry cast.

improved mechanical properties are required over die castings, or where costs must be lower than 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. ■

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