Metal Solid Freeform Fabrication Using Semi-Solid Slurries

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A new process for the direct solid freeform fabrication (SFF) of metallic prototypes and components offers a significant advantage over most other metal-SFF processes: it does not involve the use of powders, thus minimizing porosity and shrinkage distortion. This process utilizes the unique rheological and thermophysical properties of semi-solid-metal (SSM) slurries to build a near-net-shape metallic component in one step, without the need of sintering, molds, rough-machining, or post-processing operations. A stream of semi-solid is deposited over a moving substrate that follows a three-dimensional pattern. The high viscosity of semi-solid slurries and their particular rheology allows the stream to be deposited over previous layers in a controlled fashion, without traces of an interface. Because the rate of deposition is an order of magnitude faster than in other SFF processes, manufacturing is also faster. In addition, distortion problems characteristic of other processes involving fully molten metal are significantly reduced because the material deposited is already partially solid. In this paper, the first implementation of this technology is presented in detail. Eventually, this process could be useful in the production of a small series of large metallic components that would otherwise be produced by casting or machining. Those processes cost more and result in lower-quality components.

INTRODUCTION

In recent years, great strides have been made in the advancement of rapid prototyping and flexible manufacturing technology. One major need remains, however: a method to produce structural, fully dense, metallic components. Rapid prototyping is useful to generate components that physically resemble and behave similarly to the actual production component. In addition, in the case of flexible manufacturing, the component produced must satisfy functional demands. There is no doubt, then, that a process for the speedy production of metal structural components would be invaluable.

A number of solid-freeform-fabrication (SFF) processes now can address the needs of specific sectors of industry. Among them are directed-light fabrication (DLF),[1] electron-beam solid freeform fabrication (EB-SFF),[2] selective laser sintering (SLS),[3] three-dimensional (3-D) printing,[4] droplet deposition,[5] fused-deposition modeling (FDM),[6] and stereolithography.[7] Most of these processes can successfully produce components of polymer, while a few can produce components directly from metallic powders. In those processes, though, post-processes such as sintering are necessary and unwanted porosity might result. No post-processing is necessary with DLF and EB-SFF, which produce their components through localized melting. A disadvantage with those techniques is that surface tension of the molten metal dominates at the small sizes required to achieve good surface finish, creating the potential for capillary instabilities and other defects.[8,9]

With the semi-solid metal (SSM)-SFF[10,11] technique, many processing difficulties are addressed. Briefly, this method deposits a stream of SSM through a nozzle that moves relative to a substrate. Components are built by depositing the semi-solid stream in successive layers. At the completion of each layer, the substrate is lowered, and the next layer is deposited. Each layer of slurry is able to form a metallurgical bond with the previous layer, a particularly exciting capability. The technology described in this paper permits the direct, rapid fabrication of fully dense, metal structures without the limitations that are typical in the handling of molten metal.

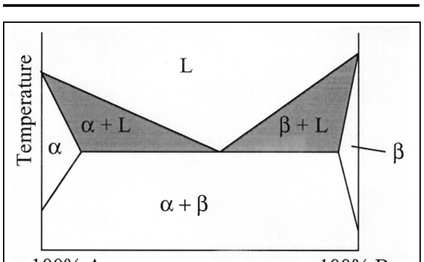

Figure 1. Sample binary-phase diagram.

SEMI-SOLID METAL PROCESSING

To understand this SFF process, it is helpful to discuss briefly the fundamentals of SSM processing.[12–15] The equilibrium-phase diagrams of metal alloys show regions of temperature and composition where a liquid phase and solid phase can coexist. In Figure 1, a simple binary-phase diagram, the shaded areas highlight these regions. During the solidification of castings in this partially solidified state, the formation and growth of dendrites is common, whether columnar or equiaxed. As the solid fraction increases past a characteristic value during cooling, the deformation resistance of the partially solidified metal increases dramatically.[14] However, if this same alloy composition is sheared sufficiently during cooling to break up dendrites and form spheroidal solid-phase particles, the deformation resistance is drastically reduced. This combination of solid-phase particles suspended in a molten-liquid phase is referred to as semi-solid slurry. Flemings illustrates that a semi-solid slurry created in this manner exhibits a shear strength three orders of magnitude lower than a dendritic system of equal solid fraction.[14] Thus, it is possible for slurries of significantly high solid fraction to flow easily.

The unique properties of semi-solid slurries can be exploited in solid freeform fabrication. For example, the flow properties of a slurry stream can be greatly modified by controlling the solid fraction present in the stream. In addition, deformation resistance, or apparent viscosity, can be changed by many orders of magnitude by changing the solid fraction of the slurry.

A typical aluminum alloy at a 10% fraction solid has an apparent viscosity of the order of 10^{-1} Pa s, similar to that of olive oil. The same alloy at a solid fraction above 50% can have an apparent viscosity of the order of 10^{2} Pa s, similar to that of toothpaste.[14]

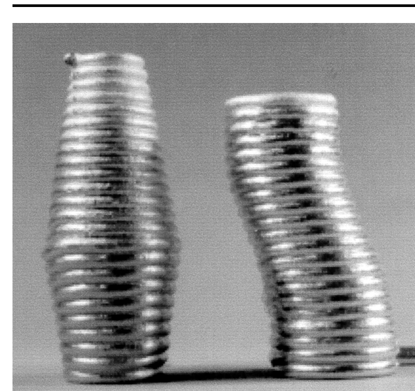

Figure 2. Sample SSM-SFF components.

PROCESS PROPERTIES AND ADVANTAGES

The use of a metal slurry allows deposition rates unattainable with a fully molten metal in other SSF processes. Also, semi-solid slurries will undergo less shrinkage during final solidification since much of the slurry is already solid and its temperature is lower. Because geometric distortion due to shrinkage and thermal stresses is a common problem in the vast majority of SFF technologies, its reduction is a valuable attribute of the SSM-SFF process.

The difference in linear shrinkage between semi-solid and liquid processing can be calculate using the following equation:

$$S_t = (1 - f_s)S_s + \alpha\Delta T$$

where S_t is the total shrinkage, S_s is the shrinkage due to solidification alone, f_s is the fraction solid, α is the coefficient of thermal expansion, and ΔT is the variation from processing temperature to room temperature. For aluminum alloy 356, $S_s \approx 1.7\%$ and $\alpha \approx 24\ 10^{-6}$ 1/K. A typical casting temperature is 700°C, and a typical semi-solid processing temperature is 580°C for $f_s \approx 50\%$. In these conditions, the total shrinkage for a liquid casting is 3.3% and for the semi-solid is 2.2%, one third less than for liquid. This implies a third less distortions due to residual stresses, as well as 50% less shrinkage porosity.

Because the components that are produced are dense metal, they can be used in structural applications where conventionally cast or machined parts would have been used. SSM-SFF is well-suited to large components because it is capable of high flow rates. In addition, the semi-solid ability to withstand its own weight allows for the deposition of thick layers (of the order of millimeters), an asset in the manufacturing of large components. The semi-solid slurry tends to flow over the previous layer immediately after being deposited. The speed at which this flow occurs is determined by the apparent viscosity of the semisolid. The time scale during which the viscous flow occurs is determined by the time to solidify the deposited stream. Dimensional analysis of this process indicates that it can be characterized by the following dimensionless group:

$$Me = \frac{\tilde{n}gtH}{\mu}$$

where ρ is the density of the semi-solid, g is the acceleration of gravity, H is the height of the stream being deposited, μ is the characteristic apparent viscosity of the slurry, and t is a characteristic time after which the viscous flow stops. Scaling of a fluid cylinder with a diameter equal to its height indicates that for small deformations $\Delta H/H \approx Me/4$; therefore, values of Me much larger than one indicate liquid-like behavior, and values much smaller than one indicate solid-like behavior. Values of the order of magnitude of one are characteristic of semi-solid. For the components in Figure 2, $\rho = 7{,}440$ kg/m^3, $t \approx 0.1$ s (time for the slurry to reach eutectic temperature), $H = 3.4$ mm, and $\mu \approx 10$ Pa s; therefore, $Me \approx 2.5$.

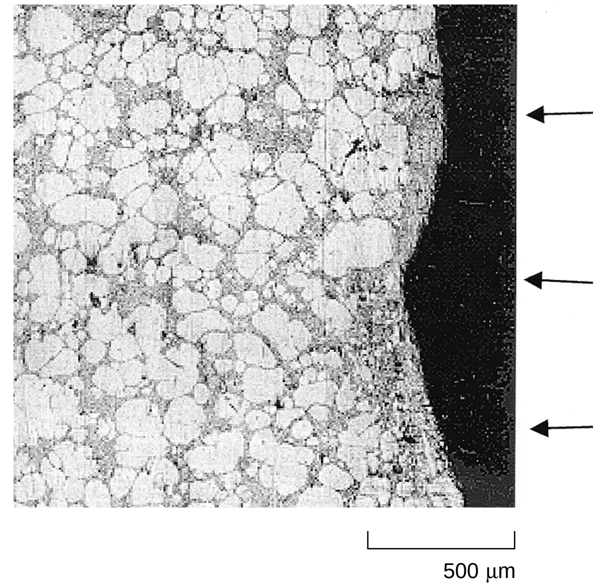

Figure 4. Metallurgical joint between two layers. The top arrow denotes a new layer, the middle arrow indicates no interface, and the bottom arrow shows a previous layer.

The capability of controlling deposition by varying the apparent viscosity is unique to this process, and it is not attainable with other technologies that involve molten metal. Only surface tension can hold molten metal in place, and this happens for Bond numbers much smaller than one, imposing an upper limit of approximately 1 mm for most metals.

Also, by controlling the solid fraction and shear history of the slurry, one can control the microstructure of the component, allowing it to possess differing material properties in different areas. Finally, once the part has been formed during deposition, no debinding, curing, hot isostatic pressing, or infiltration is needed to create a structural component.

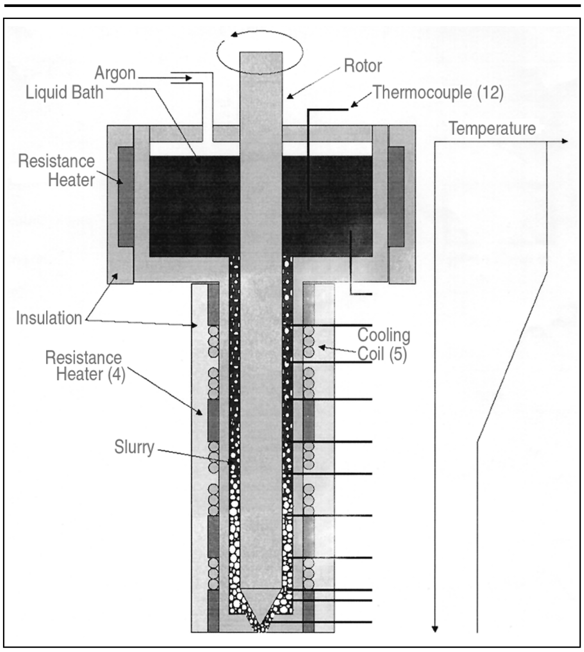

Figure 3. Schematic of the continuous rheocaster.

PROCESS DESCRIPTION

A prototype machine was built to test the concept of SSM-SFF with the model alloy Sn 85%-Pb 15%. Figure 3 is a schematic of the semi-solid production section of the system (rheocaster). This rheocaster consists of two main sections—an upper reservoir and a lower mixing chamber. The reservoir was made from large-diameter stainless-steel tubing and heated by one large, 850 W band-type resistance heater. A stainless steel plate with an argon intake valve was sealed to the top of the chamber to allow for an inert atmosphere. Its function was to contain a fully liquid alloy bath, which flowed to the lower chamber. The lower chamber, with a diameter of 5 cm and a length of 25 cm also comprised stainless tubing equipped with alternating resistance heaters and air cooling coils along its length, as shown. Numerous thermocouples inserted through the tubing into the slurry along the length of the chamber allowed precise temperature measurement and provided feedback for proportional integral derivative control of the heating elements. The tubing was insulated on the outside with an alumina-silica fiber blanket. As the molten alloy flowed from the reservoir through the length of the chamber, it was cooled to a partially solidified state and sheared by a turning rotor. The rotor was machined from stainless-steel tubing and extended the length of the apparatus. The radial gap between the rotor and the chamber was 1 mm. The bottom end of the rotor was closed with a solid tapered stainless-steel fitting to match the geometry of the exit nozzle. A conical nozzle was placed at the bottom of the mixing chamber.

A typical run consisted of the following steps: The reservoir was loaded with small pieces of alloy, and the bottom of the mixing chamber was plugged. The reservoir and chamber were then both heated to 211°C (slightly above the liquidus of 209°C[16]) while argon was flushed through the reservoir. Once the entire system was superheated, the rotor was started and set to the desired rotation rate, which typically was 70 rpm. This rotor speed caused a shear rate of the order of 200 1/s, sufficient to completely break up any dendritic growth and form rounded solid-phase particles with typical maximum dimensions of 80-100 μm. The microstructure of the solidified slurry is shown in Figure 4. Here, the solid-phase particles appear light while the lead-rich liquid phase (the liquid phase in the semi-solid state) appears dark.

Soon after starting the stirring, the lower chamber was cooled while the reservoir temperature remained above the liquidus. By flowing air through the cooling tubes and lowering the power output of the heaters, any number of possible temperature profiles could be generated in the mixing chamber. A decreasing gradient from the top of the chamber to the middle, followed by a constant-temperature regime, provided best results. The constant temperature regime was usually controlled at or around 190°C (corresponding to a solid fraction between 50% and 60%). The approximate temperature profile is shown at the right in Figure 3. When the desired temperature profile was achieved, the plug was removed to allow the flow of semi-solid.

This semi-solid stream could then be deposited on a moving substrate (Figure 5). The substrate motion was controlled by a three-degrees-of-freedom translating table. The table was driven by three stepper motors programmed to follow 3-D paths. The velocity of the substrate was generally 20 mm/s.

Figure 2 is a photograph of two components manufactured using SSM-SFF. The component on the left, a pipe section that increases and then decreases in diameter from top to bottom, is 82 mm high, weighs 290 g, and was manufactured in 60 s. The component on the right is a pipe bend section. Each would be difficult to cast or otherwise form. Geometries of these dimensions would require hours to manufacture using other SFF technologies such as 3-D printing or selective laser sintering.

The system is made versatile by allowing several variables (heating rate, cooling rate, rotor speed, and rotor clearance) to be controlled directly. Rotor clearance with the nozzle was found to affect the flow rate and could be adjusted accordingly by raising or lowering the rotor.

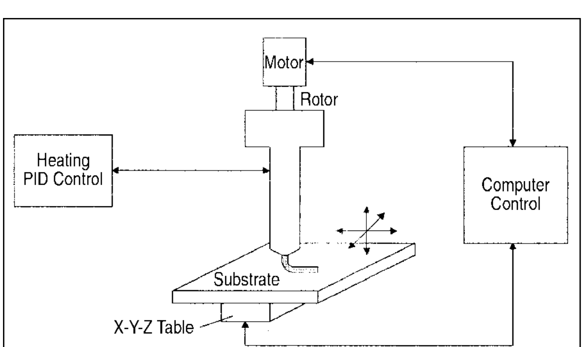

Figure 5. Schematic of deposition system.

DISCUSSION

The results presented here were obtained for a model alloy of low melting point (Sn 85%-Pb 15%). Because this alloy has no immediate industrial application for SSM-SFF, current efforts are focused on extending the capabilities of the process to aluminum alloys. A prototype machine for the production of aluminum, which is currently being tested, can produce aluminum slurries through its nozzle. Future work will concentrate on utilizing this slurry for the fabrication of aluminum components.

The adhesion between two layers depends on the temperature of the slurry being deposited and that of the underlying layer. For a good adhesion, the temperature at the interface between the underlying layer and the slurry being deposited must fall in the semi-solid regime.[17] This implies a minimum temperature requirement for the underlying layer. Because the time spent between two consecutive layers in larger components might cause the underlying layer to be too cold for an acceptable joint, a mechanism for locally preheating the substrate might be necessary. In the conditions tested, the bonding quality was as good as that of the base material, as shown in Figure 4. It is apparent that the microstructure remains constant across the layers. One can see where the layers meet at the right edge, but any sign of an interface through the cross section cannot be found. The rounded, fine-grain, solid-phase particles lead to more favorable mechanical properties than the dendritic structure typically found in castings.

A maximum angle of free overhang was found to exist during the deposition of layers. Because the orifice cross section was circular, layers tended to roll off of one another when the angle became too great. This angle was highly dependent upon the temperature of the slurry exiting the nozzle. An oriented square or rectangular orifice would help to alleviate this problem. In addition, a greater free overhang can be achieved by using collars to support the semi-solid stream.

CONCLUSIONS

Fabrication with SSM-SFF processing is significantly faster than with other freeform fabrication processes because semi-solid slurries allow for thicker layers and faster deposition rates. On the other hand, the minimum nozzle size that can carry a steady flow of slurry determines that the surface finish is coarser than that resulting from other processes. A possible commercial niche for this process would be the production of prototype or small series of metallic components or large components, such as ship propellers, that would otherwise be produced by casting or machining. Casting of large components implies the expense of fabricating models and molds. In addition, the final microstructure in a cast structure is dendritic and not as desirable as that of semi-solid, and castings are prone to defects such as macrosegregation and large pores, which are completely eliminated in SSM-SFF.

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