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3D PRINTED SAND MOLDS AND CORES USING SELECTIVE POWDER DEPOSITION

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Abstract

Three-dimensional (3D) printing of sand molds and cores has increasingly been used by foundries to produce castings with complex geometries quickly and economically. While the cost has decreased, 3D sand printing remains a relatively costly process. The technology most commonly used to produce 3D printed sand is binder jetting, a process invented in 1993 by researchers at MIT. Selective powder deposition (SPD) is an additive manufacturing technology developed to produce metal parts. In the process, unbound metal and support powders are deposited in a layer-by-layer fashion to produce the desired geometry. The build structure is then sintered or infiltrated to produce a solid metal product. The focus of this research was to determine if selective powder deposition (SPD) could be used to produce 3D printed sand molds and cores. To test this, an iro3d Model-C SPD printer was obtained and modified to print shell sand as the build medium with unbound silica sand as the support medium. The prints were cured in an oven to bind the shell sand structures. Several 3D model parts were produced to evaluate the capabilities of the printer. The structures produced included a resolution test print and horizontally parted molds. Aluminum castings were successfully produced from the molds. The results indicate that SPD can be used to economically create 3D printed sand molds and cores. This paper will detail modifications made to the SPD printer to produce 3D printed sand structures and the results obtained.

Keywords: *3D sand printing, Selective powder deposition, Shell sand*

Introduction

Additive manufacturing continues to draw a great amount of interest and innovation due to the ability to produce finished products having complex geometries with no tooling requirements. This interest has extended to the production of sand molds and cores for the foundry industry. Among the advantages of 3D printed sand molds are the ability to take a casting from concept to production in a matter of days with no need for patterns or core boxes. In addition, traditional features incorporated into designs to facilitate casting–such as draft–can be ignored with 3D printed molds,[1] reducing design time. Due to the slower rates of mold production, the economics of 3D printed sand molds are advantageous for low to medium production volumes.

The most common technology used to make 3D printed sand molds is binder jet printing in which a furan resin binder is selectively sprayed onto a bed of sand.[2] The builds progress layer by layer as additional layers of sand and binder are added to the bed. This process has been shown to produce molds with reasonably good dimensional accuracy, surface finish, and resolution. Control of the process parameters is important to obtaining desired printed sand properties.[3]

Selective laser sintering has also been used to create sand molds and cores.[4] With this technique, phenolic resin coated sand (shell sand) is spread onto a bed with uniform height before being heated by a scanning laser. The laser heats the sand and melts and cures the binder. After depositing and curing a layer, a new layer of sand is spread over bed, and the sand is once again heated by the scanning laser. The layer height is controlled by the thickness of sand spread over the bed. Results with this technique are dependent on the laser energy, scanning speed and distance, binder content, and layer thickness. Because of the non-uniform heating provided by the laser, thermal straining of the sand occurs, resulting in poor dimensional accuracy and mold strength. Post-processing of cores and molds may be required to obtain strengths comparable with traditional shell cores and molds.

Selective powder deposition (SPD) is an additive manufacturing process developed to produce metal, ceramic, and composite parts.[5] The iro3d Model-C printer (Figure 1) is a commercially available SPD machine with a build volume of 279 × 274 × 110 mm. In this process, loose build and support powders are selectively deposited in layers within a container to build unbound 3D structures. The structures are then heated and sintered (ceramic parts) or infiltrated with liquid metal to produce finished parts. Once consolidated, the parts are separated from the loose support powder. Post-processing consists of cleaning the parts or–if high precision is desired–machining. The process is versatile and can be used with a variety of materials.

To produce parts with good surface finish while also reducing build times and costs, the SPD machine only deposits fine build and support material along the outer surfaces of the part. Coarse build and support powders are used in the remaining build volume. Coarse powders are deposited using nozzles (also called pourers) with 1.9-mm-diameter orifices; while, fine powders are deposited using nozzles with 0.9-mm-diameter orifices. The recommended powder diameter is a maximum of 1/10 that of the nozzle orifice.[6] This results in a recommended sizing for the fine and coarse powders of 40–90 µm and 90–190 µm, respectively.

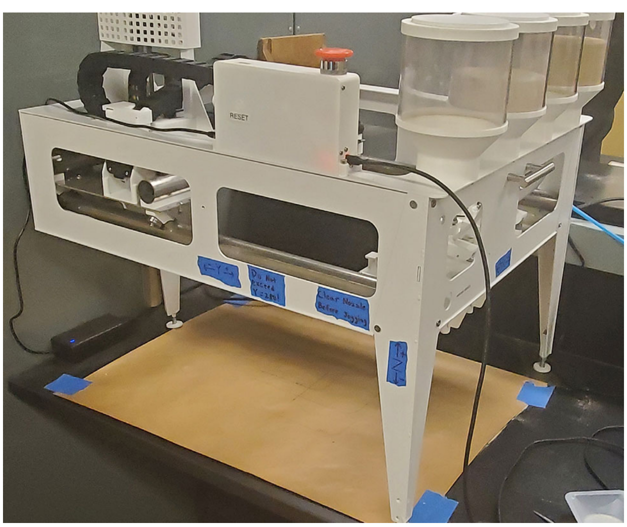

Figure 1. Selective powder deposition machine adapted to 3D sand printing.

Given the expense of binder jet 3D sand printers compared to the relatively low-cost of SPD printers, there is the potential to print sand molds at a much lower cost. This opportunity can be realized by using appropriately sized shell sand as the build material and unbound silica sand as the support material. The objective of this research was to determine if suitable shell molds could be produced using the SPD technology to make aluminum castings.

Procedure

Equipment and Materials

An iro3d Model-C SPD printer was used to produce 3D sand printed molds. The build material was shell sand (HA Super F F15G9; 3% binder); while, the support material was unbound silica sand (Covia Incast 80). A series of initial test prints were performed to determine the capabilities of the SPD printer to produce 3D printed sand molds. Initially, both the build and support sands were sized according to the manufacturer's recommendation with coarse sand being between 190 and 390 µm (− 50 + 70 mesh) and fine sand sized between 90 and 190 µm (− 70 + 200 mesh). However, shell sand could not reliably be deposited through the 0.9 mm nozzle because the shell sand tended to adhere to and clog the nozzle orifice. Therefore, only the 1.9-mm-diameter nozzles with − 70 + 200 mesh sand were used with the initial test prints. Except for the cylindrical prints (which used an appropriately sized glass beaker), the flasks used in the printing process consisted of appropriately sized aluminum baking pans. Once deposited, the sand was cured by heating in a laboratory convection oven at 200 °C for 1.5 h based on the shell sand curing test detailed next.

Shell Sand Curing Test

To determine optimum curing times and temperatures for the shell sand, tests were performed to measure the temperature in sand builds as a function of time and distance from the flask wall. The flasks used in this experiment were 11 × 11 × 3 in. In the first test, the flask was loosely filled with unbonded silica sand, while in the second test, the flask was loosely filled with shell sand. As shown in Figure 2, type K thermocouples were placed in the sand at intervals of 1 in. from the edge of the flask up to the center of the flask (5.5 in.). The flasks were placed in a laboratory convection oven preheated to a temperature of 250 °C for two hours. Temperature data were collected from the thermocouples using a data acquisition system at a minimum rate of 50 samples/s.

Test Prints

A set of preliminary test prints were made to evaluate the ability of the SPD printer to produce 3D sand prints. The test prints consisted of a hollow cylinder, a hollow egg, and a resolution test print. Modifications were made to the SPD printer after the test prints to improve its ability to print shell sand. After the initial modifications, a mold was made to produce a test aluminum casting. A second set of printer modifications ensued after this print to once again improve the printer's performance. A second aluminum test casting was poured in a 3D printed mold after these modifications to evaluate their effectiveness.

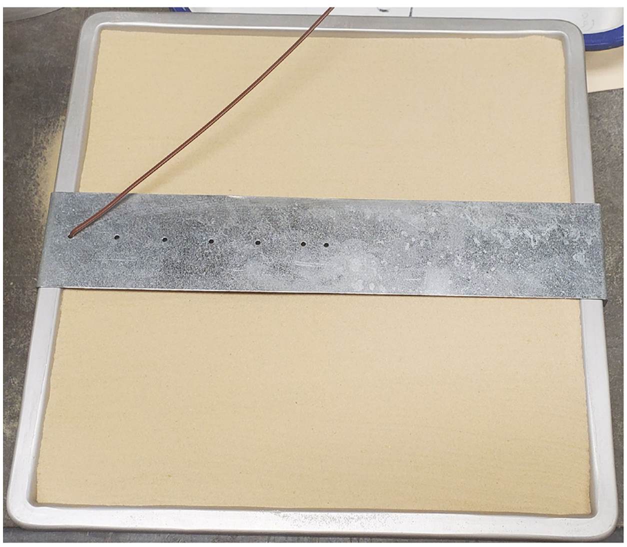

Figure 2. Flask filled with shell sand. Note the thermocouple support band across the top of the mold with the thermocouple placed in the far left hole (distance = 0 in.).

Results and Discussion

Shell Sand Curing Test

Plots of temperature as a function of time and placement for loose silica sand and shell sand are presented in Figure 3. As would be expected, sand along the perimeter of the flask heated quickly while sand near the center heats much more slowly. This thermal gradient should be taken into consideration and minimized to as great a degree as practical when curing sand molds. The exothermic nature of the shell sand curing can also be observed in the curves as the shell sand temperature for a given position and time is greater than that of the unbonded sand. The heating caused by the curing shell sand is more pronounced near the center of the flask as compared to the outer edges. For large castings, this may be used to advantage as thick sections will heat faster than would be expected without the presence of the shell binder.

Based on these results, the decision was made to cure the SPD print builds at 200 °C for 1.5 h. The lower heating temperature was expected to reduce temperature gradients within the sand to promote uniform curing.

Printer Modifications for Sand Printing

Preliminary sand prints were made to test the capabilities of the SPD printer. The first print geometry produced was that of a hollow cylinder as shown in Figure 4. This preliminary print revealed modifications that needed to be made to better facilitate printing with sand as opposed to metal powder. During initial sand printing tests, it was discovered that shell sand would often clog and not flow from the powder storage hoppers to the pourers.

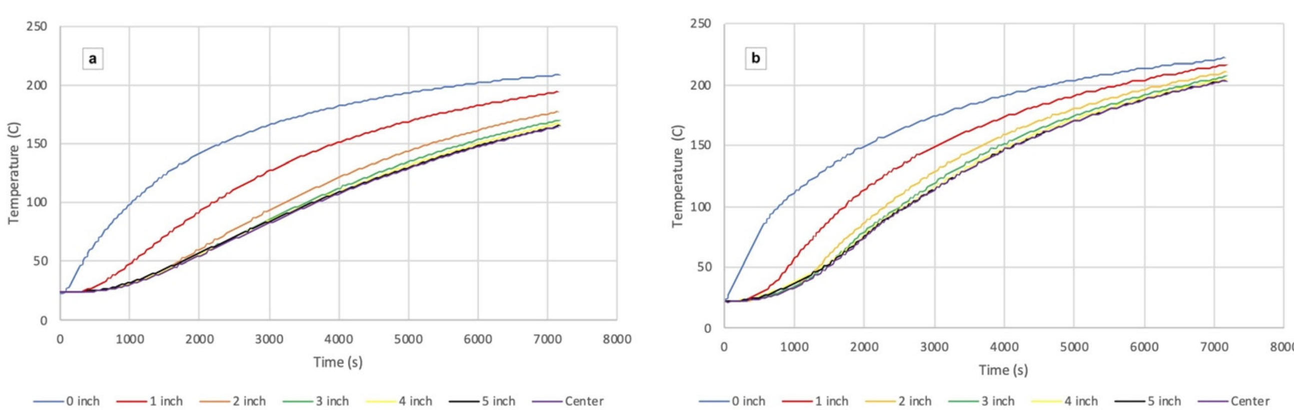

Figure 3. Temperature of unbound silica sand (a) and shell sand (b) placed in convection oven at 250°C for 2 hours.

Investigation of the cause of clogging revealed that shell sand often caked at the convergence of the hopper's conical bottom as it transitioned to the 6.4-mm (0.25-in.)-diameter transfer tube. To prevent this clogging, the diameter of the collector nozzle at the bottom of the hopper cone was increased to 12.7 mm (0.5 in) diameter to allow larger tubing (12.7 mm OD × 9.5 mm ID; 0.5 in OD × 3/8 in ID) to be used. This also required the inlet to the pourer to be modified to accommodate the tubing. This change solved the problem of shell sand clogging with the added benefit that the pourers could now be refilled more quickly; fill times were reduced from 180 s to 55 s. Based on the improved shell sand filling performance, the decision was made to modify the transfer mechanism for the support sand in a similar fashion. The decision was also made to only use the 1.9-mm-diameter pourers in subsequent prints due to shell sand continually clogging the 0.9 mm-diameter pourer. This change was achieved through settings in the printer's software.

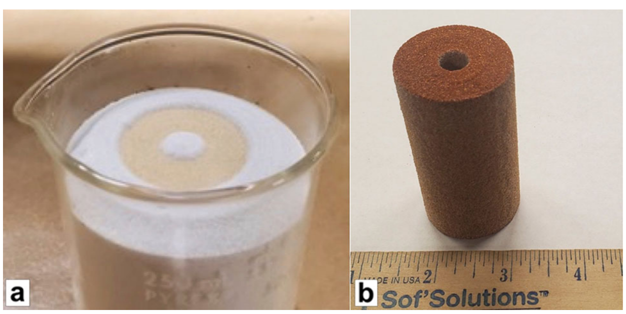

Figure 4. Hollow cylinder SPD printed in shell sand with silica support sand (a) before curing and (b) after curing.

Resolution Test Print

In order to test the printer's resolution and its ability to produce complex geometrical features, a test geometry was designed after Bryant et al.[3]. The test piece design and resulting print are shown in Figure 5. The printer was able to produce protrusion, gap, and cavity features to a good degree of accuracy. The smallest gap the printer produced in the V-groove was 1.3 mm. The largest cylindrical feature had a printed diameter of 9.2 mm vs. a design diameter of 8 mm; while, the smallest cylinder had a measured diameter of 5.4 mm vs. a design diameter of 2 mm. The largest round hole measured 7.4 mm vs. a design diameter of 8 mm; while, the smallest hole had a diameter of 4.1 mm versus a design diameter of 3 mm. The features produced were on the same order of magnitude as those of binder jet printed sand molds.[3]

Eggshell Test Print

An eggshell model (Figure 6) was printed to determine the printer's ability to accurately produce hollow geometries. The printer was able to accurately produce the hollow geometry, and the support sand was successfully removed from the eggshell interior through a small hole printed at the top of the shell. The eggshell was designed with a wall thickness of 3 mm; the printed shell thickness was 3.5 mm.

Test Casting

An aluminum test casting was produced by first printing a horizontally parted mold on the SPD printer in a 6 × 8 × 3 in. flask and then curing the mold as detailed

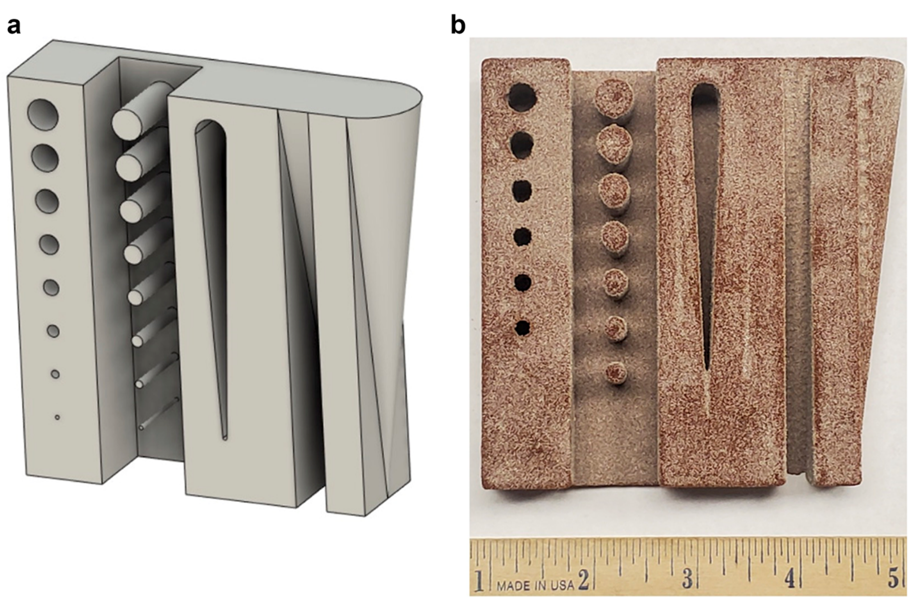

Figure 5. Resolution test piece solid model (a) and sand print (b). Hole and cylinder diameters ranged from 1 mm to 8 mm.

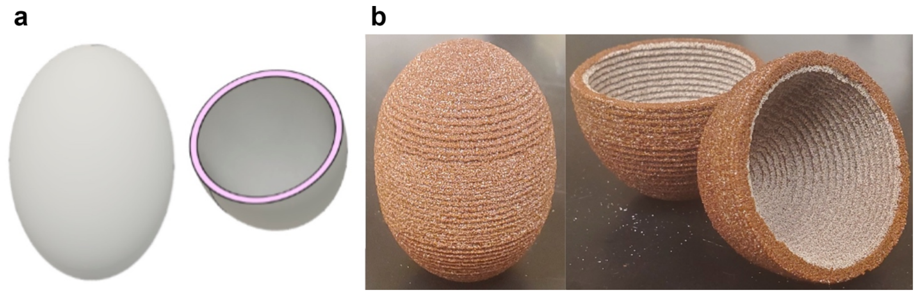

Figure 6. Eggshell solid model (a) and sand test print (b). The eggshell was later cut open to reveal the internal structure.

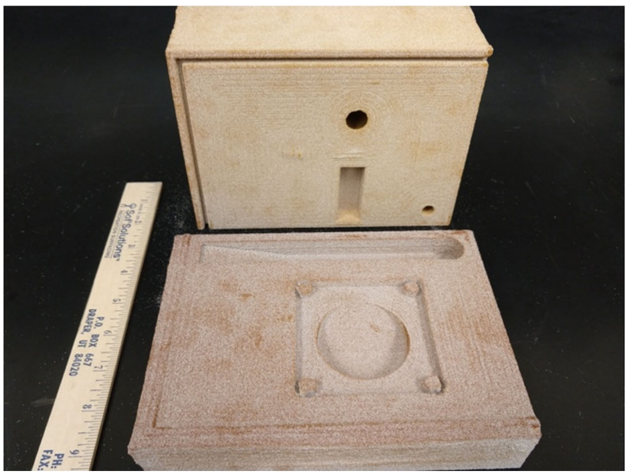

Figure 7. Cured horizontally parted mold produced on SPD printer.

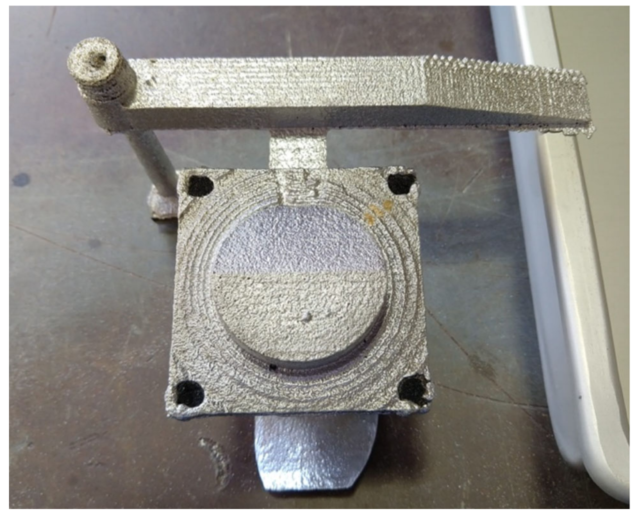

Figure 8. Test casting made with SPD 3D printed sand mold. Note the grooves around the central cylindrical feature and the incomplete holes in the corners.

before (Figure 7). Only the 1.9 mm-diameter pourers were used to deposit sand for this mold. Aluminum alloy A356 at 732 °C was poured into the finished mold. The casting was allowed to cool to room temperature in the mold before it was shaken out. After removing the casting from the mold, grooves were observed on the surfaces of the casting corresponding to the deposition pattern of the SPD machine (Figure 8). In addition, the holes intended to be formed in the corners of the casting were not properly formed. Based on these results, modifications to the printer were initiated so that a finer surface finish and better precision could be obtained. These changes are detailed next.

Final Printer Modifications and Test Casting

The manufacturer of the SPD printer worked with the research team at Texas State University to improve the surface finish of castings made from molds printed on the SPD printer. The slicer software was modified by the manufacturer to print sand mold designs more efficiently. Among the modifications was the inclusion of an adjustment of the fine pourer path overlap. Using this feature, the deposition spacing was adjusted in the slicer software so that grooves in the deposited sand no longer appeared. In addition, two pourers with larger nozzle orifices were obtained from the manufacturer. These pourers had 3.9-mm-diameter orifices that were subsequently used for coarse silica support and shell build sands. The larger orifices allowed greater build rates with their much faster pouring capabilities. In addition, larger sand sizes more typical of foundry sands could be used. Sands with diameters up to 390 µm could be used in the pourers based on recommendations to promote maximum flowability.[6]

A second test casting was made with the new slicer settings providing for a smoother surface. For this casting, fine and coarse pourers with nozzles diameters of 1.9 and 3.9 mm, respectively, were used; otherwise, the same procedure was followed as with the first casting. The improved casting is shown side by side with the first casting in Figure 9. The improvement in surface finish is apparent. The precision was also improved as evidenced by the holes in the corners of the casting being properly formed.

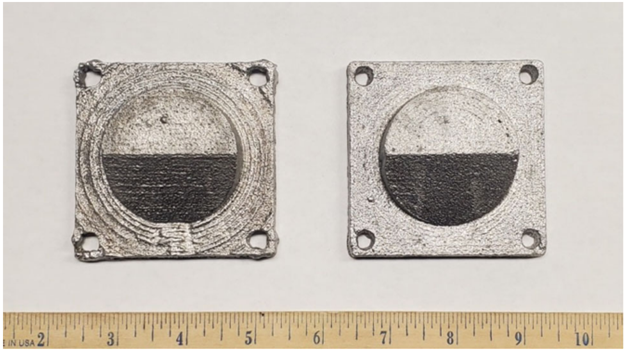

Figure 9. Castings made before (left) and after (right) printer software modifications and installation of 3.9 mm pourers.

Conclusions

The following conclusions can be drawn from this study:

1. The SPD printer can be successfully modified to deposit unbonded silica and shell sands.
2. The resolution of SPD printed sand is comparable to that of binder jet printing.
3. SPD sand printing is capable of printing geometrically complex sand molds and cores.
4. SPD printing of shell sand is an effective route to produce aluminum castings.

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