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Selective Separation Shaping (SSS) – Large-Scale Fabrication Potentials

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Abstract

Selective Separating Shaping is a new additive manufacturing technique which is capable of processing polymeric, metallic, ceramic and composites including cementitious materials. In earlier experiments the capabilities of SSS in making metallic and ceramic parts have been demonstrated. The focus of the research reported in this paper has been on exploration of capabilities of SSS for creation of large-scale cementitious composite parts. A prototype machine has been used to create specimens made of regular construction cement (lime based), Sorel cement (magnesia based) and gypsum based composites. The fabrication results, surface quality and flexural strength for these experiments are presented.

Keyword: Selective Separation Shaping, Additive Manufacturing, cementitious, composite

1. Introduction

Several AM technologies have emerged and extensive research has been carried out to extend the capabilities of the processes, improve and develop new AM materials and explore new application areas [1,2]. Current AM processes are predominantly suitable for fabrication of meso-scale objects, primarily due to the fact that the available processes use sub-millimeter layer heights which would render the fabrication of large parts impractical [3-5]. Contour Crafting is the first large-scale AM process which was invented at University of Southern California (USC) over two decades ago and its applications in constructions of terrestrial as well as planetary structures have been pursued and demonstrated [6-8]. Contour Crafting is an extrusion based AM process which started the worldwide excitement and activities in 3D printing of buildings.

A significant class of AM processes are based on powder materials and so far all of these processes have been limited to the processing of sub-millimeter powder layers [9]. Selective Separation Shaping (SSS) is a new versatile powder based AM process with demonstrated capability for building meso-scale metallic and ceramic parts [10], and now its capability to break the scale barrier in powder based processes is being demonstrated.

Based on our experiments, SSS is the first and only powder based AM process that is capable of building with layers that may be multi-centimeter thick while producing very smooth part surfaces at an unprecedented fabrication speed. Our focus in this study has been on the fabrication of cementitious composite parts and results of experiments with Portland cement, Sorel cement and gypsum are presented.

2. The SSS Process

In the meso-scale sintering-based SSS process, which has been recently reported in the literature, a thin wall of high melting point separator powder material (S-powder) is deposited within the base material powder (B-powder) to form a barrier on the boundary of each layer. This barrier creates a separation between the part and surrounding material, which allows for the separation of the part from the surrounding powder after sintering is complete. Finally, the part is removed from the platform and inserted into sintering furnace. After sintering the part is easily separated from the surrounding as the S-powder remains in powder state because of its relatively higher sintering temperature.

In the extended SSS process for large-scale part fabrication the thickness of each progressive powder layer is significantly higher than is in the case of meso-scale fabrication. Thick layers are achieved by an S-powder insertion nozzle that is thin tube with a longitudinal slot with height equal to the desired layer thickness. In the preliminary experiments a 1.30mm diameter metallic nozzle tube with a 12 mm slut is used as shown in Figure 1.

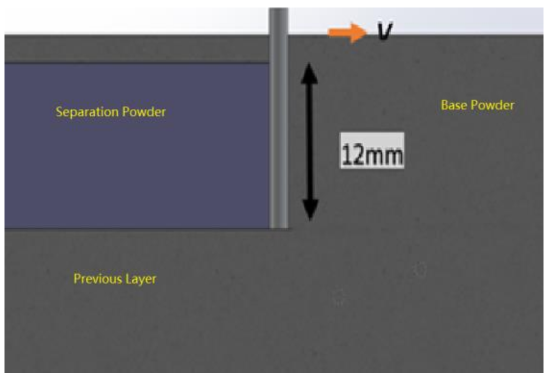


Figure 1. *Deposition of thin wall of S-powder within a 12 mm thick layer*

Unlike common additive manufacturing processes, a different slicing method is required for SSS because the process only considers part surfaces and disregards the part core. In SSS nozzle rotation is also programmed into the toolpath which traces the contours of slices.

In the first process step a uniform layer of base powder is delivered onto the build tank. The nozzle is then inserted into the base powder and the S-powder is deposited along the layer contour. The nozzle is then raised and another layer of base powder is paved over the previous layer. The process continues until all layers are processed. At this stage sufficient amount of the bonding liquid (which could be water for hydraulically activated cementitious base powders) is delivered to the top of the top layer. The liquid gradually moves down by gravity and capillary action through the entire depth of the treated section of the build tank and the part consolidation starts through chemical activation of bonding. Depending on the base material choice, the initial weak consolidation may take within one hour after which the part is strong enough to be removed from the build tank. Water (or a binder liquid) is then added periodically to the part to achieve good part strength through a more complete cement hydration process. Finally, the part is very easily separated from the surrounding material as shown in Figure 2. A brush is used to clean the extra separator material away from the obtained part.

Figure 8. *CAD model, top layer after separator powder deposition and separated part*

3. Results

Experimental parts are built with Portland cement, gypsum and Sorel cement using the beta machine shown in Figure 3. Some of the fabrication results are shown and discussed below.

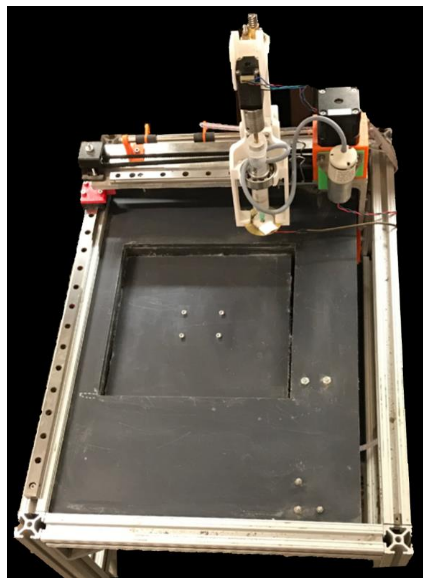


Figure 3. *Selective Separation Shaping prototype*

3.1 Portland Cement

The first material tested is Portland cement because of its wide application in Huge Construction Industry. The solidification process of hydraulic cement is complex as it involves many physical and chemical processes. Extensive effort has been devoted to finding the proper parameters for our cement curing process as in SSS curing starts right after water is added without any mixing.

Figure 4. *Single-layer (above) and double-layer (below) Portland cement parts made by SSS*

The part shown in Figure 4 has been built in 20 minutes. The thickness of the petal shape is 22 mm. The single layer outer surface is fairly good.

3.2 Gypsum

The result of building parts with gypsum (Plaster of Paris in this case) is shown Figure 5.

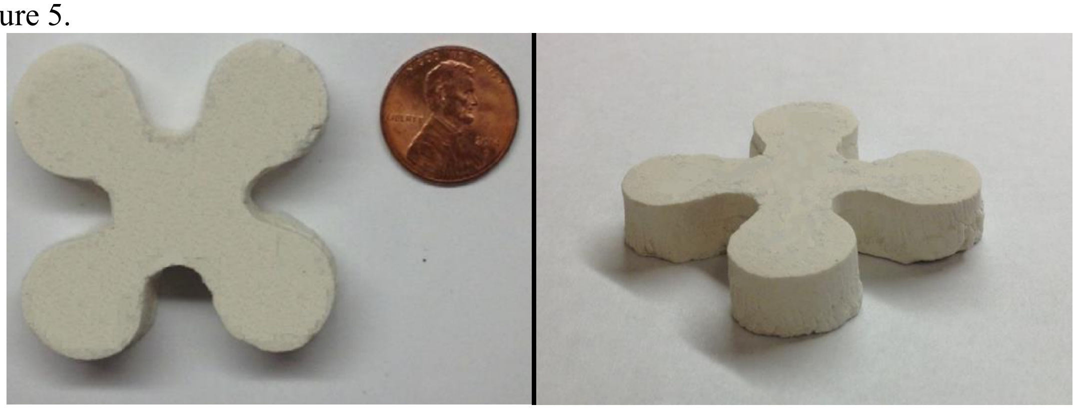


Figure 11. *Gypsum parts made by SSS*

The gypsum petal shape is 10 mm high and is made within 13 minutes. After 2 hours allowed for solidification the part is easily separated from its surrounding. The surface of some gypsum parts experience some cracks, if rapid evaporation of water content takes place.

3.3 Sorel Cement

Sorel cement, also called magnesia cement, is a widely applied cement type as it possesses properties like faster solidification and hardening speed and larger early strength. Fabrication of Sorel cement parts with SSS have been attempted and the result is shown in Figure 6.

Figure 6. *Sorel cement parts made by SSS*

Sorel cement utilized here has a combination of different size aggregates. The existence of large size particles affect the formation of separation wall, and hence negatively impact the part surface quality. Also Sorel cement is more sensitive to the proportion of water in its volume, and has a water absorption rate that is significantly less than that of Portland. Water should be added to Sorel cement powder with a well-controlled flow rate, otherwise gas bubbles may be generated which badly deform the part surface structure resulting in porous surfaces of the final part.

4. Surface Quality

The surface quality of Portland cement parts built by SSS has been studied in more detail. SSS part surface quality may be better than what can be achieved with other cement based 3D printing processes. In SSS part surfaces are of two kinds: surfaces which are created by the insertion of the separation powder and creation of the part boundary, and bottom and op surfaces which are not created by separation powder insertion.

4.1 Surface's quality interacted with separation powder

4.1.1 Impact of separation powder choice

Proper choice of S-powder can impact part surface quality considerably. A smooth and compact separation wall made of the right choice of S-powder can create smooth part surfaces. For the experiments conducted in this study soda lime is selected as separation powder because of the following favorable properties:

Firstly, with low water penetration rate, this material entraps most of the water in the base powder preventing it from easily escaping across part boundary.

Secondly, with 40 to 60 micron particle size and high stiffness, soda lime can easily generate strong capillary bridge between particles when exposed to liquid, which leads to a stronger separation wall structure post water addition. Moreover, fine separation powder size prevents the diffusion of cement slurry through the part boundary. Such diffusion can badly affect part surface quality as base powder segments outside the layer boundary may also be fused to the part.

Thirdly a separation wall made with soda lime retains most of the delivered water (or any fluid used as bonding agent) within the volume of the part thereby preventing rapid evaporation which causes cracking and allowing for a more complete curing process which results in stronger parts.

A cement part surface without any post-processing is shown in Figure 7. It can be seen that the part surface is very smooth and, as measurements have shown, geometric dimensions of the part shown have been within a few microns of target dimensions.

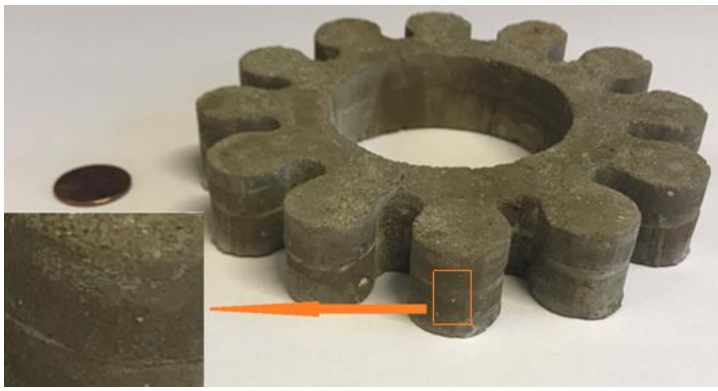


Figure 7. *A 24mm tall Portland cement part built with SSS*

4.1.2 Separation powder deposition

Even though soda lime have these good properties, insufficient separation powder deposition will limit its function. If powder deposition is not sufficient, a stiff separation wall cannot be generated or can only be generated with low quality, then soda lime's characteristics to keep products' shape and dimensions cannot take effect. In figure 8, two pictures are shown for comparison between surface with and without sufficient separation powder deposition.

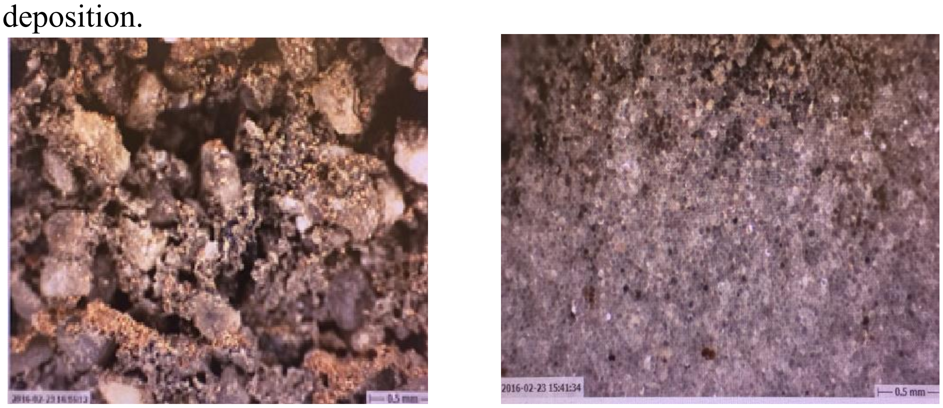


Figure 8. *Cross section of layer without and with sufficient soda lime as s powder(without on the left and with soda lime on the right)*

From the picture above, we can easily see that surfaces' quality with sufficient separation powder are much better than surfaces with insufficient separation powder.

To ensure sufficient deposition, it is critical to keep deposition powder flow stable and prevent separation powder clogging inside powder container, which is a common challenge in hopper powder flow situation [12].

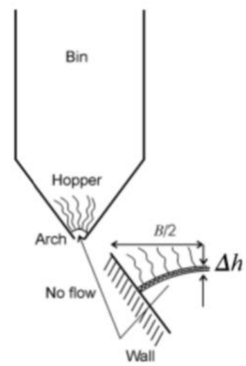


Figure 9. *Arch generation inside powder container [9]*

It is known that, under function of gravity, arch will be generated during powder's deposition in a hopper shape, which will block powder from further depositing. There are two methods to break the arch: Add air flow through bottom of hopper to blow up the arch; Add vibration to break the arch. In SSS, a combination solution is introduced as an economical and efficient solution to ensure a stable and sufficient powder flow.

Considering that hopper applied in SSS is in small size, vibration generating method is applied in the first stage. After experiments, vibration piezo with amplitude 5 microns and 3000 frequency is applied. Under this vibrating condition, arch generation can be avoided during manufacturing.

In second stage, proper air flow is chosen and applied on upper surface, other than from bottom, of separation powder in container. Experiments' result shows that this method is capable to increase low deposition rate caused by powder particle's viscosity. To obtain stable and adequate separation powder deposition, a miniature pump with proper air pressure is installed on separation powder container to provide air flow onto separation powder.

4.2 Quality of bottom and top surfaces

In the current SSS process, bottom and top surface are not covered with deposition powder but interact with the bottom machine platform plate, or with water sprayed from above the top surface, which make surface quality control rather harder.

Since water spray is impossible to be sprayed on manufacturing area exactly even and with negligible impact, it will cause uneven water distribution on powder's surface and then surface displacement.

To make water distribution even and reduce the impact of spray pressure on surface deformation, coarse sand with size ranging from 200 microns to 400 microns is used to cover bottom and upper surfaces. On upper surface, water drop will reach to coarse sand before penetrate into cement. Water can spread easily inside coarse sand, which help even water distribution in manufacturing area. In addition, sand will reduce direct impact of water spray to powder base's surface. Same sand are paved under bottom layer to prevent extra water accumulate in lower layers.

A spray system, shown in Figure 10, is also developed to generate water mist for water spraying, which is believed to be helpful to reduce water's impact. With the spray system, small water drop will be generated and spread onto powder bed, which will ensure a relatively water distribution and small impact onto base powder. All those methods are beneficial to products' surface quality. The excellent product's quality is shown in Figure 7.

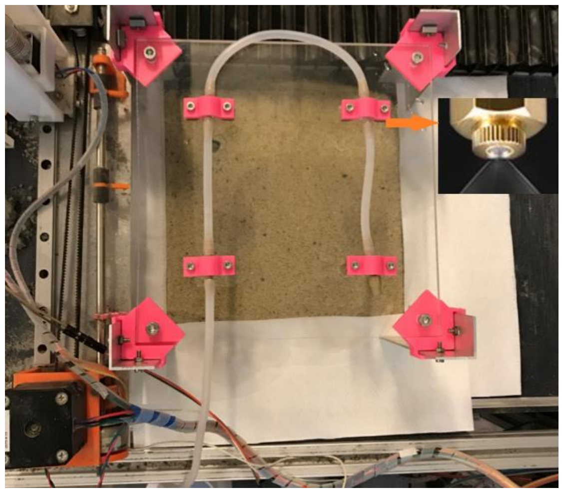


Figure 10. *A spray system with four nozzles to spread water*

5. Strength Analysis

In this section several parameters influencing cement products' final strength are discussed, and a proper process to reach high strength economically and sufficiently is introduced. Portland cement is the choice of material to be studied for achieving good strength, because cement is the most common and economical material in industry to build mega-scale and large products. Flexural test is used to determine relative strength of the specimens. This test is preferred to compressive and tensile strength test because of its simplicity.

Water/cement ratio, the ratio between water and cement's weight, is the most important parameter for cement's final strength. Water/cement ratio impacts cement's saturation level, porosity level and microstructure [13], which collectively determine product's mechanical behavior. For conventional concrete water cement ratio is usually 0.35 to 0.5. In SSS process, a specific water cement ratio is expected, because no stirring process is included in the SSS process, which may lead to insufficient water cement mixing and cement curing. Additives, like Silica fume and superplasticizer, are also considered as potentially helpful components to be added to concrete strength [14].

Maintenance during curing process is another element to affect good cement products' strength. Hydration temperature and moisture are the two most important factors in maintenance situation during curing process. An environment with proper temperature and moisture will keep cement's hydration speed within controlled level and hence reduces crack generation [15].

To analyze different parameters' effects, 7 sets of experiments have been conducted and samples' flexural strength are measured after 14 days' curing according to standard ASTM C348 **-** 14**.** The strength measurement device used is shown in Figure 11. During the measurement process, 20 by 20 by 80 mm samples are firstly fabricated by SSS machine, and force will be applied on the center of parts by a NK-500 analog force gauge after parts are fixed on a testing bed, which is shown in Figure 11.

Table 1 shows the parameter values for 7 different settings, where every experiment with the same setting is repeated three times and flexural strength is calculated as average of the results. Set 1 to 3 experiments are conducted to test samples with different water cement ratios. The material used in set 4 is a mixture of cement and sand in order to understand the effect of sand on the specimen's strength. In set 5, silica fume is added to cement where silica fume's weight is 5% of the whole mass. In set 6, a plasticizer admixture is mixed with water in percentage of 14%, and water is added into cement with water ratio of 0.4 by mass. Set 7 is a sample built with mold, where cement is stirred with water and paste is injected into a mold. In set 1 to 7, samples are submerged in pure water under 25 °C after primary curing, which is usually within 24 hours. In set 8, samples are not submerged into water to serve as a basis for comparison.

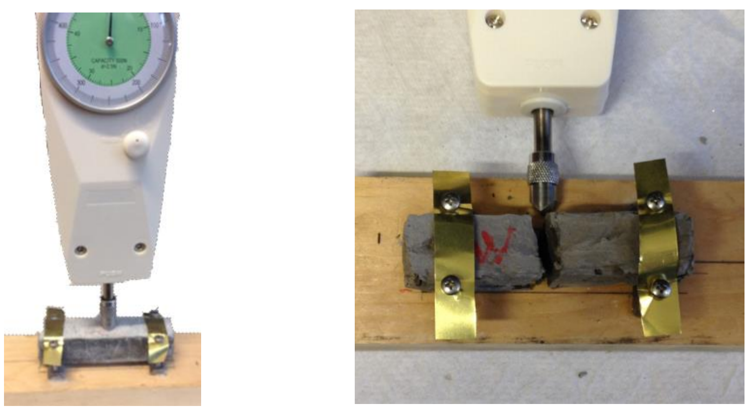


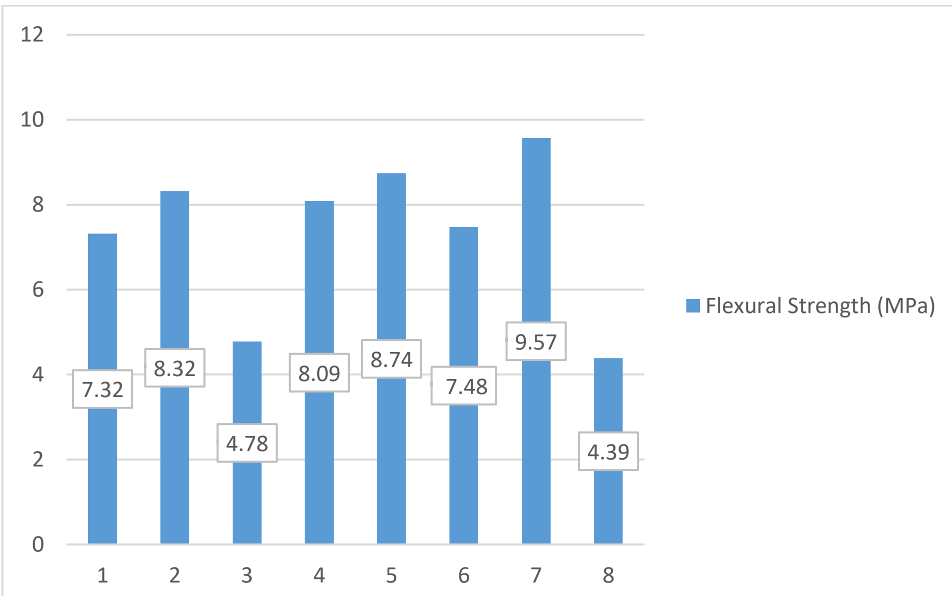
Figure 11. *Left: flexural strength measure device, right: a broken part after measure*

Table 1. *Parameter settings for strength measure*

Sample Number	W/C Ratio	Cement Agent	Percent cement	Stirring	Days Submerged	Additive	Force Applied (N)	Flexural Strength (MPa)
1	0.35	Portland	100	No	14	N/A	191.25	7.32
2	0.4	Portland	100	No	14	N/A	217.5	8.32

3	0.45	Portland	100	No	14	N/A	125	4.78
4	0.4	Portland	60	No	14	N/A	42.5	8.09
5	0.4	Portland	100	No	14	Silica Fume	228.48	8.74
6	0.4	Portland	100	No	14	Plasticizer	195.54	7.48
7	0.4	Portland	100	Yes	14	N/A	250.13	9.57
8	0.4	Portland	100	No	1	N/A	114.76	4.39

Table 2. *Mean Flexural Strength Index*



According to Table 1 and Table 2, 0.4 is the best water/cement ratio for the SSS process, and addition of silica fume and super plasticizer do not significantly increase sample's final strength. As shown in the data for set 4, the mixture with sand is a good choice if cost reduction has a high priority, because mixtures with sand do not reduce the specimen's strength. Though compared with set 4, set 7 has higher flexural strength, SSS is still considered a proper manufacturing process for cement, because samples built with SSS are 15% weaker than typical industrial concrete building methods. Filling this gap is a potential for further research. As shown in set 8, samples without maintenance process during curing are much weaker than samples curing under maintenance environment, which leads to the conclusion that our submersion maintenance process is critical to samples' strength.

6. Conclusion

A new additive manufacturing technique for large-scale construction is introduced, and its process is explained in detail. A prototype machine is developed to demonstrate the feasibility and potential of the technology. Surface quality and flexural strength of Portland cement based specimens produced by the prototype machine are also evaluated. Results of the experiments demonstrate that the Selective Separation Shaping technology has great potential in large-scale fabrication of parts out of a variety of cementitious materials. Further investigation needs to be carried out on properties of the base materials and the choice of curing agent in order to further improve part strength and obtain the desired surface quality. Application of SSS can further expand to rapid fabrication of urban structures, hardscaping, public art, building facades and pavement engineering using inter-locking tiles built in-place. SSS is also a very appealing construction technology for building structures on other planets using in-situ material. The technology has won the Grand Prize in the 2016 NASA international competition on In-situ Challenge [16]. SSS is considered to be a high-potential candidate process for construction of planetary landing pads and roads among other infrastructure elements.

Acknowledgement

SSS has been conceived and developed in the course of a Phase-II NASA Innovative Advanced Concepts (NIAC) project in relation to the part of the project that concerned landing pad construction.

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