2020

Study on the Viability of Preparing Plaster Molds for Rapid Prototyping of Complex Ceramic Parts using the Lost PLA Method

Shelton F. Fowler IV
Georgia Southern University

Recommended Citation

Fowler, Shelton F. IV, "Study on the Viability of Preparing Plaster Molds for Rapid Prototyping of Complex Ceramic Parts using the Lost PLA Method" (2020). *University Honors Program Theses*. 527.
https://digitalcommons.georgiasouthern.edu/honors-theses/527

Study on the Viability of Preparing Plaster Molds for Rapid Prototyping of Complex Ceramic Parts using the Lost PLA Method

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in Mechanical Engineering

By
Shelton Fowler

Under the mentorship of Dr. Mingzhi Xu

ABSTRACT

In the field of metal casting, cast parts often require an internal cavity to be made to meet design requirements. Frequently, these interior surfaces are not manufacturable through standard machining processes, and even when possible, they would most likely involve expensive and time-consuming operations. In order to avoid these machining costs, expendable ceramic or sand cores are manufactured and placed into the mold to allow the direct casting of complex internal geometries. This research seeks to use relatively inexpensive plastic 3D printing technology and the lost PLA casting process for the production of low-cost and rapidly producible ceramic cores. A suspension of fused silica flour in a colloidal silica binder was to be slip cast in a plaster mold and fired to create a final ceramic piece. This process has promising implications in the future of rapid prototyping of cast parts with extremely complex internal features.

Thesis Mentor:________________________

Dr. Mingzhi Xu

Honors Director:_______________________

Dr. Steven Engel

April 2020
Mechanical Engineering
University Honors Program
Georgia Southern University

ACKNOWLEDGEMENTS

I would like to thank the honors program for making this research possible. I would also like to thank Dr. Mingzhi Xu for inspiring me to do my best and for teaching me about the joys of metal casting. I would like to thank him for his constant mentorship and guidance throughout the research process.

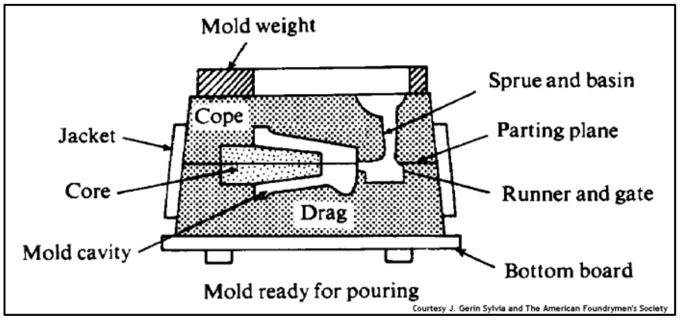
I would also like to thank my family and friends who helped shape me into the answer-seeking person that I am today. Without them I wouldn’t have made it this far.

1. INTRODUCTION

The purpose of this study was to investigate the viability of using the lost PLA process for the rapid production of ceramic parts with an emphasis on their use in the metal casting industry. Several properties of the ceramic parts were to be tested and optimized to allow for a usable final product.

1.1 CASTING CORES

In the metal casting industry, finished castings often require a certain internal geometry that can range from simple to exceedingly complex. The more complex the internal geometry is, the more cost prohibitive it is to simply machine the required features; even in the age of CNC machining, some cavities are just impossible to machine due to tooling or size restrictions. More complex cavities require the use of expendable sand or ceramic cores to form a cavity in the piece that requires minimal post-processing [1].



Courtesy J. Gerin Sylvia and The American Foundrymen's Society

Figure 1. Diagram of a Two-Part Sand Mold with a Core [2]

Figure 1 shows a typical sand mold in which a core would be used [2]. The core is placed on the parting line forming the negative of the interior geometry. The figure's core is fairly simple for demonstration purposes, but cores can become extremely complex depending on the required geometry.

Standard cores are produced using mold boxes and thus face the same limitations that all cast and molded parts face; they're limited in complexity and must have a positive draft angle for easy mold removal [1]. Like standard cast parts, as complexity increases the need for inserts and expensive tooling also increases. For low run or prototyping purposes, it's often not feasible for companies to expend the cost for tooling that won't be in use for long or for a product that may not work.

There are several 3D printing technologies that are capable of producing complex ceramic and sand parts for use as cores. SLS (selective laser sintering) printers are able to use a high-powered laser to melt together layers of fine ceramic powder to form three dimensional parts. The second type of 3D printing technology is known as binder jetting and it involves binding together fine layers of sand with a polymer spray. Both of these technologies accomplish the same objective but can be cost prohibitive for smaller companies or projects, often running from $500,000 to $1 million.

1.2 SLIP CASTING

Slip casting is a widely used technique in the pottery and ceramics field. This process involves using a relatively simple two-part plaster mold and a ceramic slurry to cast a thin walled ceramic piece.

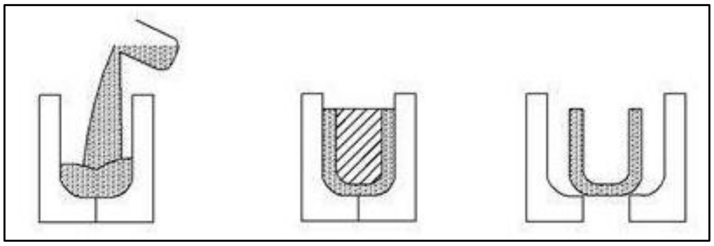


Figure 2. Diagram of the Slip Casting Process

The process of slip casting is shown in detail in Figure 2. To begin, a slurry of water and a fine ceramic powder is poured into a hollow cavity in the middle of a two-part mold; however, these molds are not strictly limited to two parts but may have additional sections to provide for more complex features in the casting. The slurry is poured into the mold and allowed to sit until enough water is absorbed by the plaster to form a tough, leathery skin around the interior of the mold cavity. The remaining slurry is then poured out and the green (unfired) ceramic piece is demolded for final firing [3].

Slip casting faces the same problems as most casting in that geometry is fairly limited without the use of complex setups and inserts. The complexity is especially limited in slip casting as the plaster used for the mold is quite fragile and not conducive to thin sections and small parts.

1.3 LOST PLA PROCESS

As 3D printing technology has progressed, printing has become more accurate and more accessible and several innovations have been made using this technology. PLA or polylactic acid is a type of bioplastic that's commonly used in fused filament fabrication (FFF) 3D printing, the most common type of printing; its relatively low melting point and high strength make it well-suited for this application.

In recent years, lost PLA casting has become a more commonly used technique by both hobbyists and professionals for the investment casting of complex metal and glass parts [4]. The lost PLA process involves encasing a plastic 3D print in a plaster or ceramic shell and then firing it at high temperatures to burn out the plastic. Much like the lost wax process, the mold positive is consumed and leaves behind little to no residue or ash. The final result is a cavity that is most often filled with some sort of molten material and then allowed to cool before the mold is broken and the piece is removed.

Lost PLA does not face the same limitation as traditional casting processes. The geometry of the piece is essentially limited by the capability of the 3D printer used because the printed piece is consumed and therefore does not have to be removed from the mold prior to pouring the metal. Also, unlike die casting, there is no need to consider how to remove the final part from the mold because the mold shell is expendable as well; it is simply broken or washed off after metal solidification.

The theory is that combining the above techniques could allow for the efficient creation of economical complex ceramic parts for use as casting cores. The lost PLA process could be used to create plaster molds with complex geometry which could be used to slip cast final silica parts.

2. LITERATURE REVIEW

2.1 EXISTING TECHNOLOGIES

Several studies have been done on the use of additive manufacturing in the production of ceramics. The main type of 3D printing technology used in ceramic printing is binder jetting. In a study done on the effectiveness of binder jetting for the creation of sand molds, a binder jetted sand mold was compared to a traditionally prepared sand mold for metal casting [5].

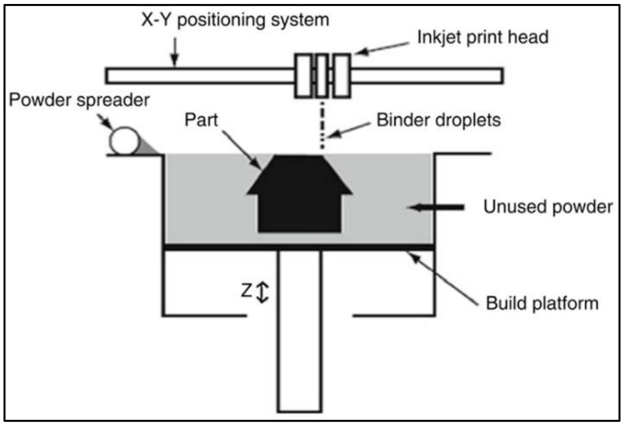


Figure 3. Binder Jet Process Diagram

Figure 3 shows how the binder jet printer in the study worked. Thin layers of sand were deposited and then bonded together with a fine jet of furan resin, a common sand binder in the casting industry. While not specifically a core for casting, the mold material is essentially the same as what would be used for a core in the industry. The study showed that the mold was capable of much higher precision and surface finish than conventional sand molding, but the cost of the machine was quite a bit higher at $250,000 [5]. Therefore, this technology might be cost prohibitive for smaller companies or projects with limited resources.

Another widely used technology for ceramic 3D printing is selective laser sintering (SLS) which is similar to binder jetting but uses a high-powered laser to selectively melt fine layers of ceramic powder and a polymer binder together. A study of different ceramic printing technologies compared SLS and binder jetting technologies for the production of ceramic pieces [6]. The study found that SLS printing had several post-processing steps that rendered it more unreliable binder jetting printing. Firstly, a high temperature final sintering was needed after the laser sintering to prepare the part for usage. This higher temperature firing allows the ceramic grains to more tightly bond and form a more solid part [7]. The problem found in this study was that at these elevated temperatures, the structure of the part softens and becomes susceptible to deformation even under its own weight. This reduces dimensional stability and makes the technology unreliable in applications that demand high precision [6]. In addition, SLS machines have a high cost and are expensive to operate and maintain.

A new technology similar to FFF 3D printing has also been tested by researchers as a more cost-effective alternative to SLS or binder jet printing [8]. The technology is similar in that a substance is extruded and selectively deposited layer by layer to build a 3D model. In the study, the researchers used a suspension of a fine alumina powder in a methylcellulose solution to form a paste-like substance that was then extruded in layers through a computer-controlled pressurized nozzle. The researchers then removed the final green body from the bed and sintered it to form the final ceramic part. The overall process was successful, but the prints were highly sensitive to the viscosity of the paste and experienced a 6%-7% shrinkage upon sintering [8]. These properties would make it difficult to design for the close-tolerance applications required by some castings. A related technology explored in another study involves a traditional 3D printing approach by using highly filled polymer filaments [9]. These filaments are similar to standard FFF filaments, but they contain particles of a certain ceramic or metal that allows for the plastic to be debonded after printing, leaving the metal or ceramic behind. The resulting body is then sintered and used in the application for which it was designed. This process has several disadvantages as the filament is often finicky and difficult to print with; along with this, the green body remains susceptible to deformation during the final sintering, much like SLS produced parts [9].

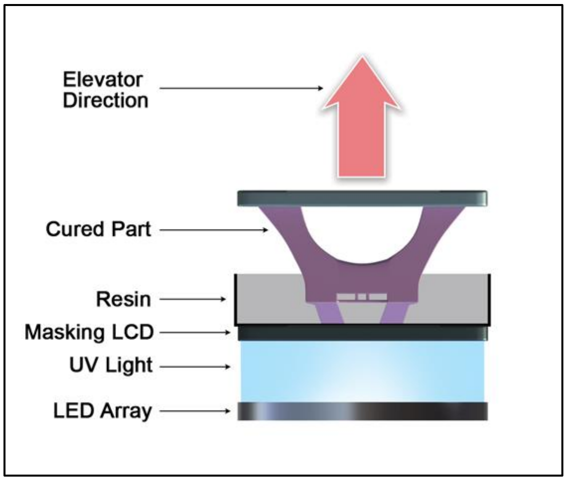


Figure 4. SLA Printing Diagram

The final kind of direct to ceramic 3D printing technology is ceramic stereolithography (SLA). These printers utilize a high-resolution screen below a vat of photopolymer resin that selectively cures areas of a model layer by layer as shown in Figure 4. Researchers have explored the possibility of using a photopolymer resin with a suspension of fine ceramic particles [10]. This technique allows for the creation of extremely complex parts due to the nature of SLA printing but has disadvantages much like the previous technologies mentioned. The prints created are still in a green state and must be sintered to form the final part; because the ceramic is suspended in a polymer matrix, the prints are susceptible to warping when heated. This warping mainly affects unsupported thin sections, having a negative impact on final accuracy of the product. In addition, the polymer burnout is an unreliable process that becomes increasingly difficult as the section thickness increases; incomplete combustion could greatly impact the final strength of the ceramic part [10]. Companies such as Formlabs have released ceramic suspension resins to the commercial market with the purpose of consumer prototyping of ceramic parts. These resins are impacted by extremely high amounts of shrinkage, around 15%, during firing which makes them inadequate for precision manufacturing [11].

2.2 PRIOR RESEARCH

Little research has been done in the use of 3D printing for slip casting ceramic parts. Researchers in Argentina have done some work with preparing two-part plaster molds using 3D printed patterns [12]. They used a two-piece icosahedron that was split across the midline to produce both sides of the plaster mold. A slurry of white clay slip was then poured into the plaster cavity and allowed to sit for 20 minutes; this allowed for the water in the slurry to be absorbed through capillary action into the plaster mold. The green shell was removed from the plaster and then bisque fired. After bisque firing, the researchers coated the pieces in glaze and did a final firing, although this step would not be necessary if the parts were to be used as casting cores. The final glazed firing softened the corners and affected the dimensional stability [12].

This research verified that 3D printing is a viable technology for making plaster molds, although the standard limitations of molding still apply with this technique. Because a two-part mold was made, the draft angle of the parts is still limited to only positive surfaces. A successful use of the lost PLA method would allow for any level of complexity to be achieved.

3. METHODOLOGY

Fluidity of the slurry is important as it determines the finest detail or section size that can be made with the slip casting process. To evaluate the fluidity of the slurry with various concentration of ceramic powder, a fluidity test block was designed as shown in Figure 5. The test block was 3D printed in PLA to assess the minimum section thickness achievable by different slurry viscosities. The thicknesses to be tested ranged from ¼ inch at the thickest down to $^{1}/_{16}$ inch at the thinnest, as seen in Figure 5. Air vents were modeled to allow air to escape as the slurry was poured in.

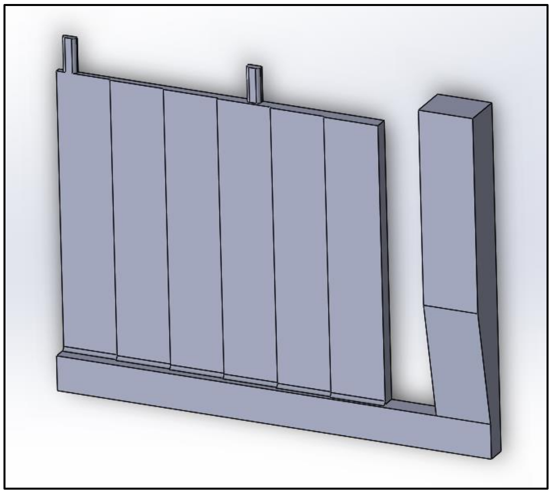


Figure 5. Fluidity Test 3D Model

Three fluidity patterns were initially printed and embedded in a block of USG no. 1 pottery plaster, the standard plaster used for slip casting molds. Once dried, the plaster block containing the fluidity tests was demolded and placed into an oven at 700°F for four hours to facilitate complete burnout of the PLA.

Figure 6. Initial Fluidity Test Block After Burnout

After burnout, it was found that the plaster was severely cracked due to the heat and thermal expansion of the PLA patterns inside, although the plastic was successfully burned out, leaving only a small amount of residue on the walls. Figure 6 shows the extreme amount of cracking throughout the plaster mold. The mold was rendered useless for testing and another sample would have to be prepared with a different plaster.

Research showed that plaster of Paris was found to have a higher maximum temperature than standard pottery plaster, so a small-scale test was run to determine the heat resistance of plaster of Paris. Small blocks of the pottery plaster and plaster of Paris were poured and allowed to cure before being placed into an 800°F oven for three hours. The plaster of Paris was found to fare much better than the pottery plaster, although minimal cracking still occurred.

The next step of the research would have been to prepare new fluidity tests and perform the tests on three different ratios of a fused silica slurry. The slurry was to be a mixture of fine silica flour and an aqueous colloidal silica binder in three different ratios. The control slurry would have been mixed to the manufacturer's recommended ratio while the other two fluidity tests would have been with a slightly higher amount of binder and a slightly lower amount of binder; this would allow for a less viscous slurry and a more viscous slurry respectively. The slurry would have been poured into the fluidity test's downspout and allowed to sit until completely dry.

After fluidity testing, the next step would have been to demold the tests from the plaster. After the elevated temperature of the burnout, the plaster should be brittle enough to allow for a clean release of the fragile green ceramic part. The part would then be sintered at 800-900°C and then tested for density, strength, and dimensional accuracy.

4. RESULTS AND DISCUSSION

4.1 FINDINGS/EXPECTED RESULTS

The research found that the plaster that is usually used for slip casting is not adequate for this process; the temperatures required are far too high and calcination of the plaster leads to excessive cracking. Plaster of Paris is a more promising replacement and it is expected that it would be a viable way to slip cast, but further research should be done to determine this. Plaster of Paris also still had problems with cracking at high temperatures; this could be due to the expansion of the 3D prints or to high temperature sensitivity of the plaster itself.

Due to extenuating circumstances, the experiment presented in the paper was not able to be completed, although it is expected that this method would work as described. With a successful plaster mold, it is certainly feasible that a ceramic slurry could be cast much like molten metal. With this technique, the contraction rate should be fairly minimal compared to other ceramic 3D printing technologies due to the lack of the polymer binder that is used in every other process.

4.2 FUTURE WORK

It is possible that the green ceramic piece would not stand up to the strain of being demolded from the plaster; in that case a small-scale test would be run to determine if the ceramic could be sintered while still in the plaster mold. This would be ideal for the end product as the part would be supported by the mold during the firing and would be less likely to warp. The plaster would also degrade heavily at the temperatures required for ceramic sintering, allowing for easier demolding after the firing was complete. However, it is possible, although unlikely, that the silica part would bond with the plaster mold, making this option impossible. Further testing should be done to determine whether this is a possibility.

Future research could also explore the possibility of using a stronger plaster that is designed to withstand high heats and large amounts of expansion such as an investment plaster; however, it is possible that this plaster has additives that would not make it conducive to slip casting. Further tests may experiment with plaster fillers such as combustible filaments for higher strength before burnout and lower strength after or a high temperature fiber to maintain strength in the mold even after firing.

5. CONCLUSION

The process described in this paper seems to be a viable solution for the rapid prototyping of ceramic cores. It would allow for a quicker, cheap way to produce complex ceramic parts with only a standard plastic FFF 3D printer and a furnace. This technique, if successful, would be an attractive alternative to smaller companies without the ability to afford specialized machinery.

REFERENCES

[1] Campbell, John. 2015. *Complete Casting Handbook : Metal Casting Processes, Metallurgy, Techniques and Design*. 2nd ed. Butterworth-Heinemann. https://bit.ly/3bgZY04.

[2] St. Paul Foundry. St. Paul Foundry. n.d. https://www.stpaulfoundry.com/DesignGuide/processes.aspx (accessed April 8, 2020).

[3] Krasnyi, B., T. Marinina, and A. Galganova. “Some Features of Porous Permeable Ceramic Molding by Slip Casting.” *Refractories & Industrial Ceramics* 56, no. 3 (September 2015): 292. doi:10.1007/s11148-015-9833-1.

[4] Sarmiento, Jeffrey. 2019. “Graphic Swim: 2D and 3D Printing in Glass Casting.” *Arts (2076-0752)* 8 (1): 29. https://bit.ly/34I6tXt

[5] Hawaldar, Nishant, and Jing Zhang. 2018. “A Comparative Study of Fabrication of Sand Casting Mold Using Additive Manufacturing and Conventional Process.” *International Journal of Advanced Manufacturing Technology* 97 (1–4): 1037. doi:10.1007/s00170-018-2020-z.

[6] Yun YU, Tingchun SHI, Yonghui MA, Fangfang SUN, Jinde PAN, and Yong YANG. 2020. “Study and Application Status of Additive Manufacturing of Typical Inorganic Non-Metallic Materials.” *Materials Science / Medziagotyra* 26 (1): 58–70. doi:10.5755/j01.ms.26.1.18880.

[7] Chen, An-Nan, Jia-Min Wu, Kai Liu, Jing-Yan Chen, Huan Xiao, Peng Chen, Chen-Hui Li, and Yu-Sheng Shi. 2018. “High-Performance Ceramic Parts with Complex Shape Prepared by Selective Laser Sintering: A Review.” *Advances in Applied Ceramics: Structural, Functional & Bioceramics* 117 (2): 100. doi:10.1080/17436753.2017.1379586.

[8] Tang, Shiyan, Zitian Fan, Huoping Zhao, Li Yang, Fuchu Liu, and Xinwang Liu. “Layered Extrusion Forming—a Simple and Green Method for Additive Manufacturing Ceramic Core.” *International Journal of Advanced Manufacturing Technology* 96, no. 9–12 (June 2018): 3809. doi:10.1007/s00170-018-1712-8.

[9] Gonzalez-Gutierrez, Joamin, Santiago Cano, Stephan Schuschnigg, Christian Kukla, Janak Sapkota, and Clemens Holzer. “Additive Manufacturing of Metallic and Ceramic Components by the Material Extrusion of Highly-Filled Polymers: A Review and Future Perspectives.” *Materials (Basel, Switzerland)* 11, no. 5 (May 18, 2018). doi:10.3390/ma11050840.

[10] Halloran, John W. "Ceramic Stereolithography: Additive Manufacturing for Ceramics by Photopolymerization." *Annual Review of Materials Research*, July 2016: Vol. 46:19-40.

[11] Scott, Clare. "Formlabs Releases Ceramic Resin, Nervous System 3D Prints Beautiful Jewelry with It." *3DPrint.com*. May 16, 2018. https://bit.ly/3biuCX4 (accessed April 8, 2020).

[12] Velazco, DPC, et al. 2014. “Rapid Prototyping of a Complex Model for the Manufacture of Plaster Molds for Slip Casting Ceramic / Rapid Prototyping of a Complex Model for the Manufacture of Plaster Molds for Ceramic Barbotina.” *Ceramics* 60 (356): 465–70. doi: 10.1590 / S0366-69132014000400003.