Design & Development of a 3D Sand Mold Printer for Rapid Casting

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Declaration

I certify that this research work titled “*Design & Development of a 3D Sand Mold Printer for Rapid Casting”* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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MASTER THESIS WORK

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Acknowledgements

I am thankful to my creator Almighty Allah, the most beneficent and the most merciful, for giving me the intellect so used in the course of this project and for guiding me through each and every step of the project. Indeed nothing is possible without his divine decree. I could have done nothing without his priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Allah Subhana-Watalas will, so indeed none be worthy of praise but him.

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Abstract

The traditional sand casting begins with the manufacturing of a physical pattern which is then used to develop a mold. The process however may require a lead time of days, or even weeks sometimes, depending on the size & complexity of the part to be cast. Furthermore, the foundry has to deal with the storage of the pattern so that it can be used again to make a new mold when a new batch of production or order is placed again. The foundry is actually paying to have them warehoused. It also requires a great skill and a lot of effort and time is wasted for making a pattern and small mistakes results into complete loss of pattern and it has to be made again.

To address the issue different techniques have been developed out of which a promising one is Additive Manufacturing. The technique in principle joins materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing. While the process has been used for rapid prototyping, its application in the field of manufacturing of sand molds for direct casting is rather new and unexplored. It holds quite a promise to reduce the lead times of cast parts since it can create complex and accurate sand cores and molds directly from CAD data, thereby eliminating the need for a physical pattern.

The research carried out hence focuses on the determination of the factors which affect the printability of a sand mold and the Design and Development of a 3D Sand Mold Printer using locally available/used sands and binders. The setup developed makes use of inkjet printing technology to spray the binder on the sand layers. The process begin with distributing a fine layer of sand, pre-mixed with the catalyst, and followed by spraying binder in the selected area of the deposited sand layer. Curing reactions taking place make the sand particles stick together only within the region where the binder will be sprayed. The process is repeated as the platform moves downward by a set distance until all of the layers of the part are completely printed and a final sand layer is spread.

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List of Abbreviations

CAD - Computer Aided Design

3D - Three Dimensional

STL - Standard Tessellation Language

GFN - Grain Fineness Number

CISS - Continuous Ink Supply System

CNC - Computer Numerical Control

PF - Paper Feed

IPA - Isopropyl alcohol

CHAPTER 1: INTRODUCTION

1.1 Casting – An Overview

Casting is the most basic manufacturing process to manufacture products made up of metals. It is the process in which molten metal is poured into a mold which contains a hollow cavity of the desired shape and then allowed to solidify. The solidified part is also known as a casting which is then ejected or broken out of the mold depending on whether the mold is permanent or expendable. It is most often used for making complex shape and intricate shapes that would be otherwise difficult or uneconomical to make by other manufacturing techniques.

There are many types of casting techniques such as;

i. **Investment Casting:** Investment casting as referred to as lost-wax casting is used to produce high quality castings. It derives its name from the fact that the pattern is invested or surrounded with a refractory coating as is suitable for repeatable production of net shape intricate components.

ii. **Sand Casting:** It is the metal casting process characterized by using sand as the mold material.

iii. **Permanent Mold Casting:** It is the metal casting process in which reusable molds, usually made from metal, are used. It is typically used for the high volume production of simple metal parts.

iv. **Centrifugal Casting:** It is the metal casting process in which molten metal is poured into a permanent mold as it spins at high speeds around its axis.

v. **Continuous Casting:** It is a refinement of the metal casting process for the continuous high-volume production of constant cross-section metal parts. It allows lower-cost production of metal sections with better quality due to standardized production of a product.

Out of these sand casting is one of the most popular and simplest types of casting and has been used for centuries as it allows for smaller batches than permanent mold casting at a very reasonable cost. Based on the type of sand and binding agents used, sand casting is further divided into green sand molding, dry sand molding, no bake sand molding, cold box molding etc.

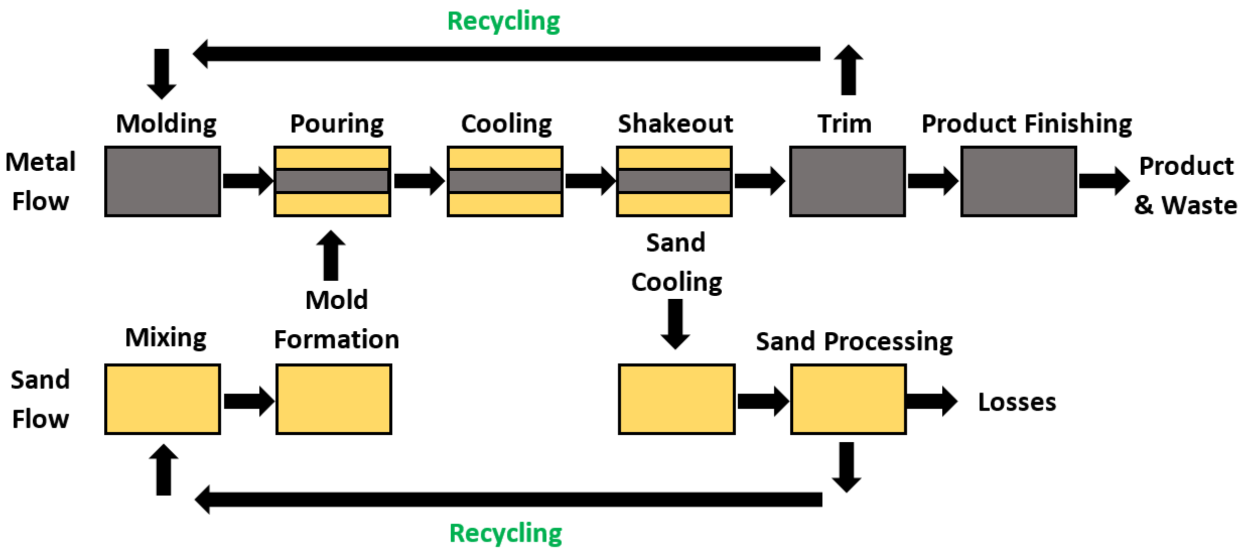


Figure 1 Sand Casting Process Flow Chart

1.2 Research Problem

In this modern age of manufacturing shortening of lead times for product development is the one of most pressing issues in production. To achieve industrial productivity and competitiveness, reduction of manufacturing lead time and increased flexibility of manufacturing is necessary. For sand casting, the traditional process begins with manufacturing a physical pattern which is then used to develop a mold. This process however may require a lead time of days, or even weeks sometimes, depending on the complexity of the part to be cast.

Different techniques have therefore been developed to address the issue out of which Additive Manufacturing, also known as 3D printing, is one. The technique in principle joins materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing. While the process has been used for rapid prototyping, its application in the field of manufacturing of sand molds for direct casting is rather new and unexplored [1]. It holds quite a promise to reduce the lead times of cast parts since it can create complex and accurate sand cores and molds layer by layer directly from computer aided design (CAD) data in a short period of time, thereby eliminating the need for a physical pattern.

The processes that are capable of producing sand molds and cores include laser sintering and 3 dimensional printing (3DP), with the latter additive manufacturing process growing in dominance over the former. Furthermore, the 3D printing of sand molds by binder jetting technology for rapid casting plays a vital role in providing a better value for the more than thousands of years old casting industry by producing quality sand molds economically. The parts of the mold assembly can be manufactured by precisely controlling the process parameters and the gas producible binders within the printed mold. A variety of powders, of different particle size or shape, and bonding materials can be used and a functional mold can be manufactured with the required mold properties such as gas permeability, strength, and heat absorption characteristics [2]. The process hence ensures a high success rate of quality castings with an optimized design for weight reduction.

The importance of 3D printing to produce complex sand molds has increased substantially in the last two decades as casting companies are starting to buy large scale commercial 3D sand mold printers. However, limited studies have been carried out currently to understand the relationship between the characteristics of the printed mold, the materials used, and the processing parameters for making the mold. Most of the material supply is controlled by machine manufacturers and thus it is difficult for academics to experiment with different materials and to determine their properties. Furthermore, most works have focused on the printers which use powder of plaster-ceramic composition. Other systems using various sand (e.g. Chromite, Silica, Zircon, or Ceramic Beads) - binder (furan or phenol) - catalyst systems may provide better properties, especially due to the lower binder content than the earlier system [1].

1.3 Objective

The broad aim of this research project is to develop a working lab scale 3D sand mold printing setup using layer deposition & drop jet technology that can be furthered researched and worked on. A breakdown of the objectives of the research is as follows;

i. To study the existing procedures used for the production of sand molds in the local foundry.
ii. To review the literature available related to the 3D printing of sand molds & to obtain the contemporary knowledge about the different mechanisms used.
iii. To find and select suitable binders/catalyst for the working prototype.
iv. To design and develop a sand layer deposition platform & compaction mechanism.
v. To reverse engineer an existing inkjet printer for binder dispersion.
vi. To determine and recommend future work.

1.4 Organization of Thesis / Phases

This thesis report consists of a total of five chapters. In chapter 1, an overview of casting, the research problem and objective of the research is presented. Chapter 2 discuss the different types of sand molds, the different additive manufacturing technologies and the relevant literature available for the 3D printing of sand molds. The chapter also discusses the findings from visits conducted to the local foundries. Chapter 3 covers the methodology for the selection of materials, proof of concept and the development of the lab scale working prototype. Chapter 4 discusses the results obtained from the testing of the developed setup while the final chapter, chapter 5 concludes the research and recommends future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Additive Manufacturing

Additive Manufacturing is a term which refers to a group of production techniques used to fabricate a physical part or assembly by depositing material drop by drop or layer by layer as opposed to subtracting material using three dimensional computer aided design (CAD) data. The geometrical CAD model is sliced into layers and a single two dimensional layer is deposited in the specified shape of the of the part model. Continuous deposition of layers one after another in the end results in the production of a 3 dimensional part with the required geometry.

Like every other technology additive manufacturing has its strengths and its weaknesses and is not always the right choice. It has distinct pros and cons and careful consideration should be done to decide if additive manufacturing is the best process for the required product. Following are some of the prominent advantages and disadvantages of additive manufacturing.

2.1.1 Advantages

i. **Free complexity:** It actually costs less to print a complex part instead of a simple cube of the same size. The more complex the faster and cheaper it can be made through additive manufacturing.

ii. **Easy revision**: In traditional manufacturing, modifying a design during production can lead to significant cost increases or time delays as tooling on a production line is changed out. In additive manufacturing parts can be modified on the original CAD file in seconds, and reprinted without complicated tooling changes

iii. **Reduced assembly components:** Moving parts can be printed in directly into the product which can significantly reduce the quantity of components in the assembly.

iv. **Reduced lead time:** Prototypes can be printed with a 3-D printer immediately after finishing the part’s stereo lithography (STL) file. As soon as the printing is done the parts can undergo testing rather than waiting for weeks or months for a prototype or part to come in.

v. **Reduction in weight:** Additive manufacturing systems can produce structures with higher strength-to-weight ratio as compared to completely solid structures.

vi. **Lower wastages:** rather than producing an end product by taking material away, additive manufacturing adds to it instead leading to lower material wastages (if any).

vii. **Lower energy usage:** As compared with traditional manufacturing processes, additive manufacturing can significantly reduce energy usage by using less material and eliminating the steps from the production process.

2.1.2 Disadvantages

i. **Slow build rates:** Additive manufacturing processes usually have slow build rates as compared to traditional techniques.

ii. **Poor quality:** The surface finish and dimensional accuracy may be of a lower quality as opposed to other manufacturing techniques and may require some post processing.

iii. **Limited size / volume:** The products size / volume is limited to the build area of the machine. While larger machines are available, they tend to be quite a bit pricey.

iv. **Poor mechanical properties:** The end products may have poor mechanical properties and defects because of the layering and multiple interfaces.

While the process of additive manufacturing has been used for rapid prototyping, its application in the field of manufacturing of sand molds for direct casting is rather new and unexplored. Fig-2 shows the increasing trend of the research and publications in the field of additive manufacturing as well as 3D sand mold printing [1].

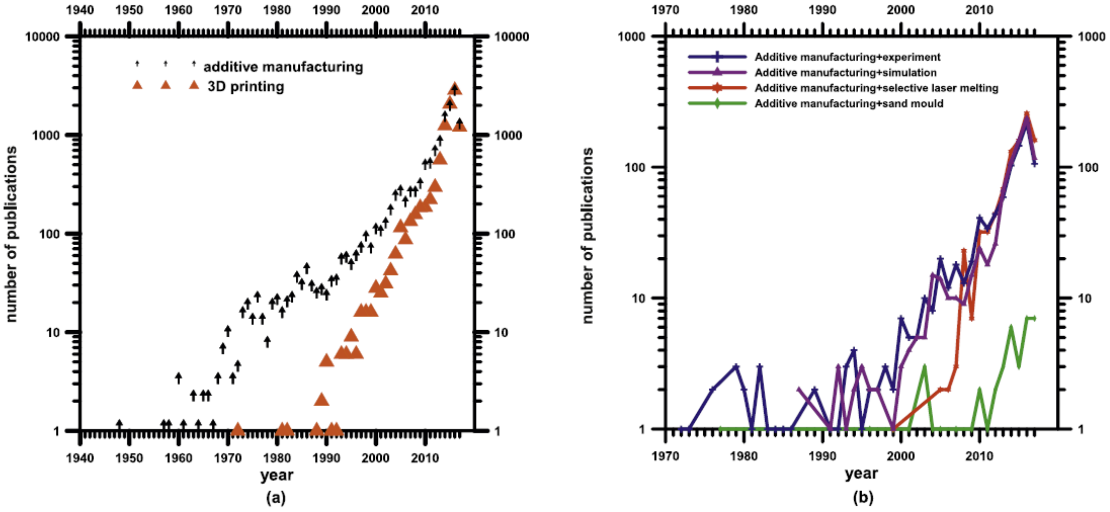


Figure 2 Growing trend in the number of scientific research publications on additive manufacturing and 3D sand mold printing

2.1.3 Types

There are various additive manufacturing methods that are being used by the industries to construct parts or geometries. Some of the most widely known are discussed below [3];

i. **Stereolithography:** Also known as VAT photo-polymerization and is a laser-based technology that uses an ultraviolet (UV) light is to cure or harden the resin corresponding to a cross section of the product, whilst a platform moves the object being made downwards after each new layer is cured [4].

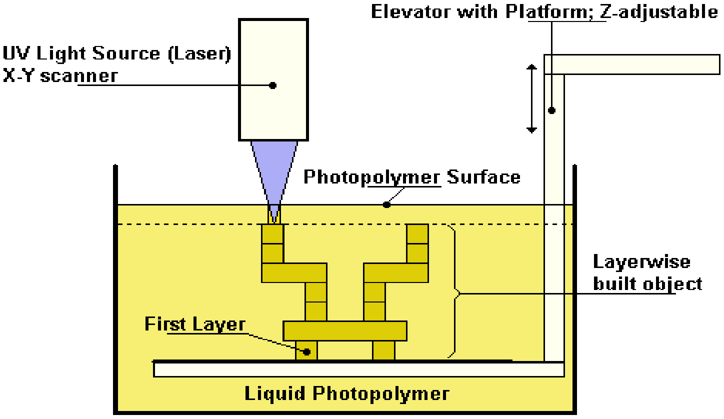


Figure 3 Stereolithography Process

ii. **Fused Deposition Modelling:** It is the most recognizable printing method in which heated material is extruded through a nozzle and onto a build plate. The nozzle continuously moves around, extruding the melted material at a precise location, where it instantly cools and hardens. Layer by layer the part builds up [5].

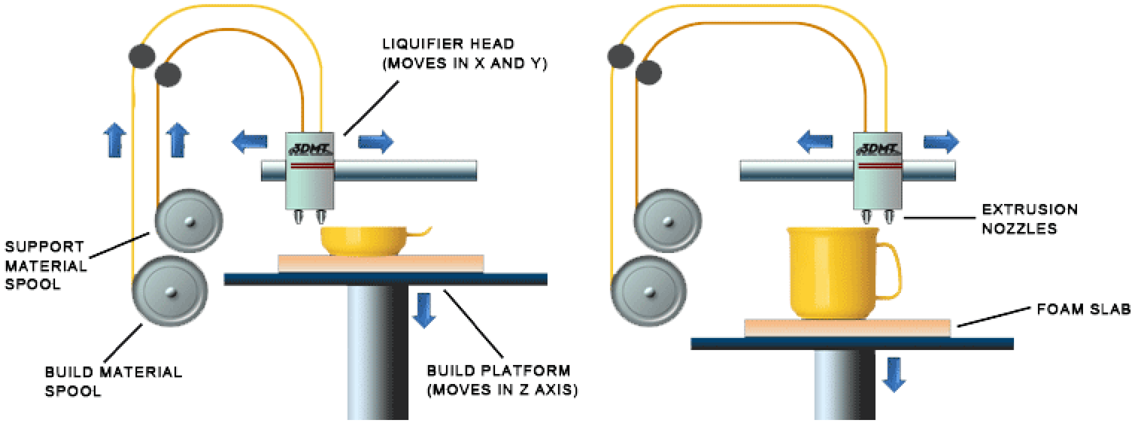


Figure 4 Fused Deposition Modelling Process

iii. **Selective Laser Melting:** Selective laser melting is an additive manufacturing process that works on the principle of melting and fusing powders through a laser. The usage of the laser ensures that the printed part is in high accordance with the CAD model and has high surface finish and accuracy. The costs however associated for setup and the fabrication of the parts is considerably high. It is used in the casting industry to produce sand or ceramic molds for castings that give high porosity and strength.

iv. **Selective Laser Sintering:** The process is almost similar to selective laser melting in basic concept. The slight difference is that the powder isn't melted but sintered giving rise to differing properties. The process never actually consolidates the material; instead, the laser simply allows the particles to merge unlike melting which actually creates a pool where the materials can consolidate before reforming and hardening to create a new solid structure.

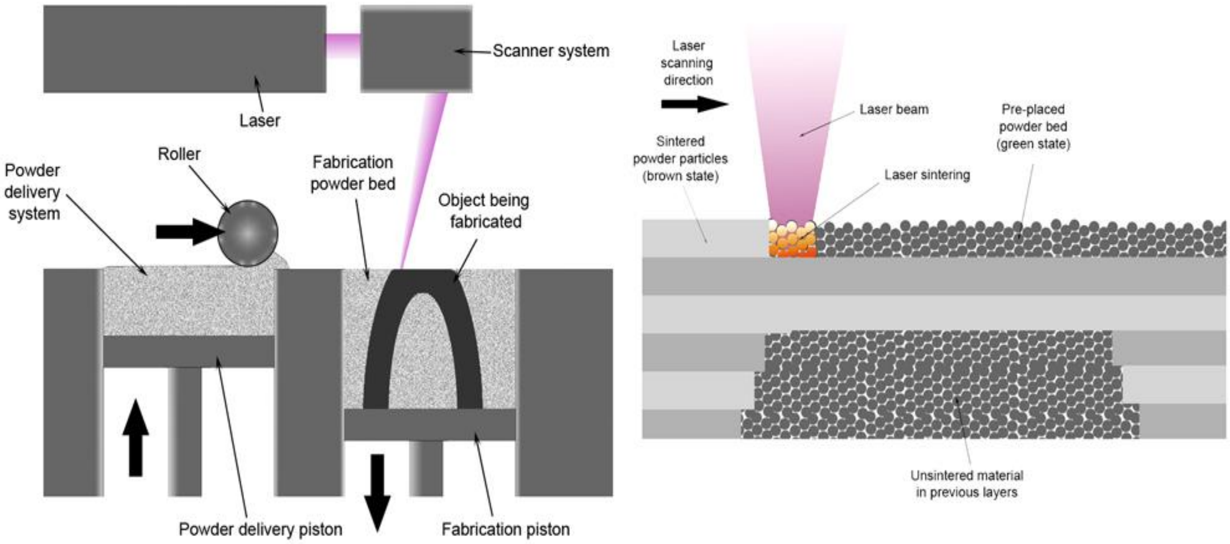


Figure 5 Selective Laser Sintering Process

v. **Powder Bed Binder Jetting:** Powder bed binder jetting printing makes use of the inkjet printing technology and uses two materials; a powder based material and a binder. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. The process begin with distributing a fine layer of the powder which is followed by spraying binder in the selected area of the deposited sand layer. Curing reactions taking place make the particles of the powder stick to each other only in the selected areas where the binder was dispensed. The process repeats itself as the platform moves downward by a set distance until all of the layers of the part are completely printed and a final powder layer is deposited [1]. The remaining unbinded powder still remains loose is brushed off leaving only the finished product.

One major advantage of the process is that there is no need for supports because the powder bed itself provides this functionality. The parts however resulting directly from the machine are not as strong as compared to other techniques and require post-processing to ensure durability.

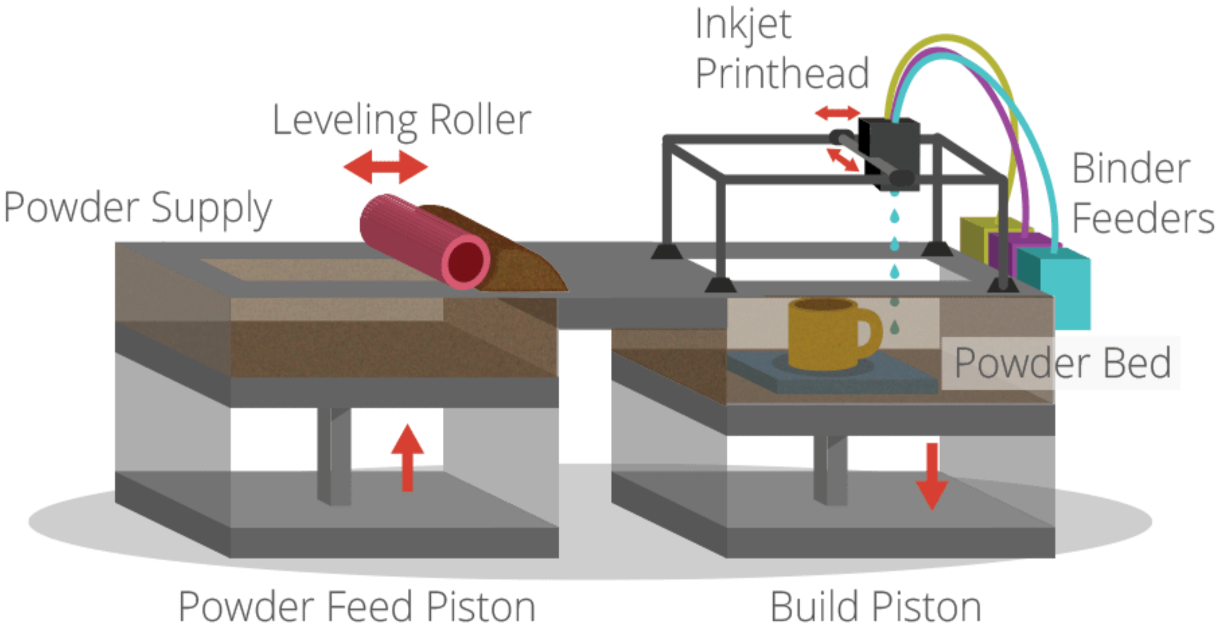


Figure 6 Powder Bed Binder Jetting Process

2.2 Sand casting

Sand is the most widely used of all the casting process because the sand offers several benefits to the casting process. The sand itself is very inexpensive and can withstand high temperatures, allowing metals with very high melting points to be cast easily. It however has a low production rate because the expendable mold must be destroyed in order to remove the final casting.

2.2.1 Types

Depending on the preparation of the sand, the sand molds can be characterized into the following distinct types;

i. **Green Sand Molds:** Green sand molding is a process of making molds with three essential ingredients - Sand, clay and water. It is called green sand as the mold is used green without drying. Typical composition of the mixture is 90% sand, 3% water, and 7% clay or binder. These types of sand molds are the least expensive and most widely used.

ii. **Skin Dried Molds:** A skin dried mold is basically a green sand mold with added bonding materials which is dried to remove the moisture and to increase the mold strength. Doing this also improves the dimensional accuracy and surface finish but will lowers the collapsibility of the mold. These types of mold are comparatively more expensive as compared to green sand molds.

iii. **Dry Sand Molds:** Dry sand molds also known as called a cold box molding is the process in which the sand is mixed with an organic binder and is strengthened by baking it in an oven.

iv. **No Bake Molds:** In no bake sand molds the sand is mixed with a resin and catalyst mixer and the curing reaction takes place at room temperature. As a result the cured mold can immediately be used for casting.

2.3 Local Visits & Surveys

The local foundries were visited to gather information about the techniques employed by the local industry for the making of sand molds. The information gathered is briefly summarized below;

2.3.1 Small Scale Local Foundries

There were no standard quality procedures employed in the small scale local foundries. The molds were made out of sand obtained and sieved from the river bed and using water and molasses as a binder. They were also not aware of the 3D printing of sand molds technology.

2.3.2 KSB Pumps (Hassan Abdaal):

KSB Aktiengesellschaft is a universal supplier of pumps, valves and related services having one of its manufacturing facilities located in Hassan Adbaal under the name of KSB Pumps. They have been one of the leading providers in their field for over a 100 years.

The manufacturing facility is an international standard foundry having proper quality control and testing procedures to ensure quality castings and sand molds. Following is some of the information gathered during the visit;

i. Sand with a specified moisture content and having an GFS Grain Fineness Number approximately equal to 55 is used for the sand molds whereas the Grain Fineness Number is a method for expressing the average grain size of a given sand sample.
ii. Two types of binders were used for the preparation of sand. One was an undisclosed organic binder for cold box sand mold making and the other was a Furan no bake resin with a sulfuric acid based initiator. However due to the highly toxic nature and strongly pungent smell of furan resin, proper care and handling was required. Furthermore, the resins and binders were specially imported from Germany since they are not available in local market.
iii. Sand mold hardness, sand mold permeability, grain fineness number, moisture content test and metallurgical tests were some of the tests conducted to ensure the quality of the molds and castings.
iv. Some of the higher management were aware of the 3D sand mold printing technology.

2.3.3 Excel Engineering (Lahore):

Excel Engineering a part of Excel Group of Companies is located in Shahdrah Lahore. It is fully equipped with state of the art engineering tools and produces high quality standard automotive and engineering products including casting. The foundry section develops a range of complex sand castings and cores using different materials like sodium silicate, resins and molasses.

The company in the past years have used a furan no bake resin for its sand castings however due to the environment unfriendly and toxic nature of the resin they switched to an alkaline phenolic binder. The resin is specially imported from Jinan Shengquan Group Share-Holding Co., ltd

(China) since it is not available in the local market. Following are the features, application procedure and the precautions for the alkaline phenolic resin;

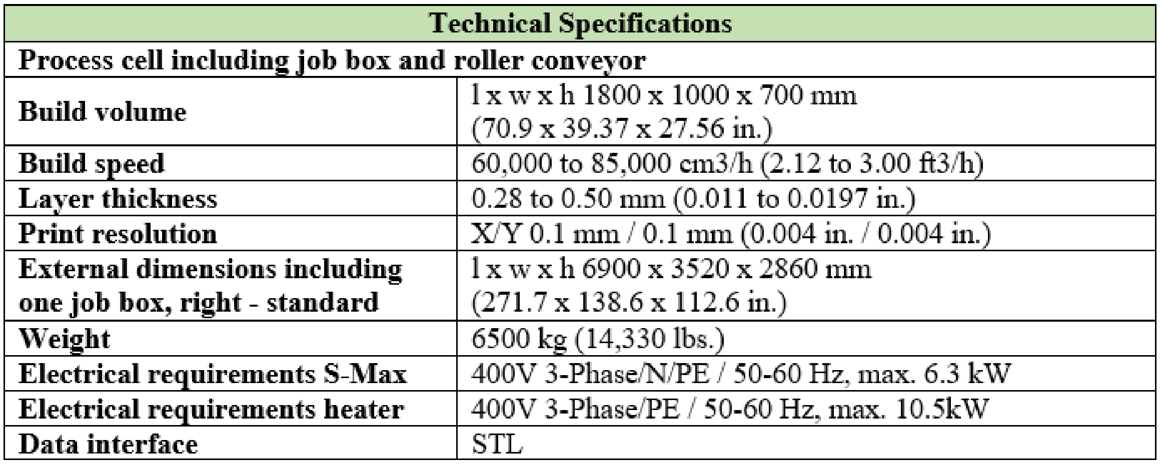
i. **Features:** The alkaline phenolic no bake resins are a brownish-red transparent liquid cured with and organic ester.
    - Resin contains no nitrogen, and the hardener is free of phosphorous and sulfur greatly reducing surface and subsurface defects.
    - The resins thermoplastic properties and secondary high temperature hardening process reduce hot tear and veining defects in steel and ductile iron castings.
    - Improved plant working environment as a result of no noxious or irritating odors during sand mixing, core production and pouring.
    - Excellent shakeout characteristics contribute to the overall efficiency of the process.

ii. **Application Guide:**
    - The sand is mixed with the hardener first and then with the resin.
    - Approximately 1.2 – 2.0% resin by weight (based on sand) is added to the sand along with 20-25% hardener by weight (based on resin).
    - Typical mixing time is 5 to 10 minutes. Different types of hardeners or hardeners with different curing speed can be used to adjust the curing speed.

iii. **Precautions:**
    - Resin – It is corrosive to eyes, respiratory system and skin. Wear protective gloves, [protective clothing, eye protection, face protection. In case of contact with skin remove all contaminated clothing and wash with plenty of soap and water.
    - Resin – Provide local exhaust or general room ventilation to minimize dust and/or vapor concentration. Keep away from kindling, heat source and oxidizer. Keep the container well sealed.
    - Hardener – It may be irritating to eyes. Handle in accordance with good industrial hygiene and safety procedure. Ensure prompt removal from eyes, skin and clothing.
    - Hardener – Provide local exhaust or general room ventilation to minimize dust or vapor concentrations. Keep away from kindling and heating source.

2.4 3DP of Sand Molds Using Additive Manufacturing

There have been advancements in the field of 3 dimensional printing of sand molds using additive manufacturing techniques over the last decade and a few commercially available 3D printer from companies like Voxeljet & EXONE have made their way into the local market. The setups however are quiet expensive and the applications and results are limited to specialized materials. Regardless of the company all the printers however make use of the powder bed binder dispersion technology for the making of sand molds because it can produce optimized parts for weight reduction. Figure 7 shows the technical specifications of a commercial 3D sand printer from ExOne.



Technical Specifications	
Process cell including job box and roller conveyor	
Build volume	l x w x h 1800 x 1000 x 700 mm (70.9 x 39.37 x 27.56 in.)
Build speed	60,000 to 85,000 cm3/h (2.12 to 3.00 ft3/h)
Layer thickness	0.28 to 0.50 mm (0.011 to 0.0197 in.)
Print resolution	X/Y 0.1 mm / 0.1 mm (0.004 in. / 0.004 in.)
External dimensions including one job box, right - standard	l x w x h 6900 x 3520 x 2860 mm (271.7 x 138.6 x 112.6 in.)
Weight	6500 kg (14,330 lbs.)
Electrical requirements S-Max	400V 3-Phase/N/PE / 50-60 Hz, max. 6.3 kW
Electrical requirements heater	400V 3-Phase/PE / 50-60 Hz, max. 10.5kW
Data interface	STL

Figure 7 ExOne's S-MAX 3D Sand Mold Printer

Various factors play an important role in the 3D printing of sand molds. These factors include, type of sand, grain size, binder properties, hardener properties, binder saturation, layer thickness, layer compaction, curing time, printing speed, droplet size, build orientation of job box etc. Table 2 presents the binders, properties and applications of some of the 3D printed sand molds used for casting.

Table 1 Binders, properties and applications of some of the 3D printed sand molds

Powder	Particle Size	Suitable Binder	Properties	Heat Treatment	Application
Plastic Ceramic Composite		Zb56		190^{o} C for 4-8 h	Non-ferrous metals
Chromite, Silica	140/190/250µm	Furan or Phenol	250 - 300 Ncm^{-2}	None required	Non-ferrous metals
Silica, Zircon, Chromite,	140/190/250µm	Phenolic	250 - 300 Ncm^{-2}		Ferrous metals
Ceramic Beads		Furan			Grey iron & steel

The following discussion presents a review of the research already carried out on some of the factors which is available in the literature;

- Research shows that an increase in the binder saturation level for a constant layer thickness results in an increase of the tensile and flexural strengths of the molds specimens. This is however associated with a decrease in dimensional accuracy and surface quality [6].
- Research shows that an increase in the layer thickness for a constant binder saturation results in the decrease of the tensile strength and increase of the flexural strength. It also gives a better quality uniform surface [6].
- The density and surface roughness of 3D printed parts is found to be decreased in certain powder and binder combinations as compared to traditional sand molds.
- The 3DP process provides higher flexibility in the printing of the mold with the requisite runners and riser system along with the cores. Studies have shown that binder jetting process fabricates parts in shorter times with dimensional tolerances. The volume of production and the geometries complexities also have a marked effect on the costs for production.

- New powder layers can be deposited using a scrapper or a roller. A scrapper only deposits a new layer without any additional compaction while a roller also provides added compaction. The compaction further depends on the direction of rotation, speed or rotation and feed of the roller. Each technique has its advantages and disadvantages however a counter rotating roller is preferred because it creates an even and flat layer and since a forward rotating one is more prone to disturbing the new powder layer [7].
- According to a research conducted by Yaser Shanjani & Ehsan Toyserkani at the University of Waterloo (Canada), the relative densities shown in figure 9 and figure 10 can be obtained by analyzing the counter routing compaction of powder with the 1 dimensional slab approach [7]. The results however shown are valid for the following analysis parameters;
    - Friction coefficient between loose powder and underlying compacted layer = 0.5
    - Friction coefficient between roller and powder = 0.3
    - Roller radius (R) = 10mm
    - Initial powder density ($\rho_{initial}$) = 30%
    - Upper bound angle of roller (α_{in})= 0.2 radian

Whereas,

H_s = rolling gap

V = linear roller motion

ω = rotational speed

R = Roller radius

P_r = Roller pressure

α = Roll angle

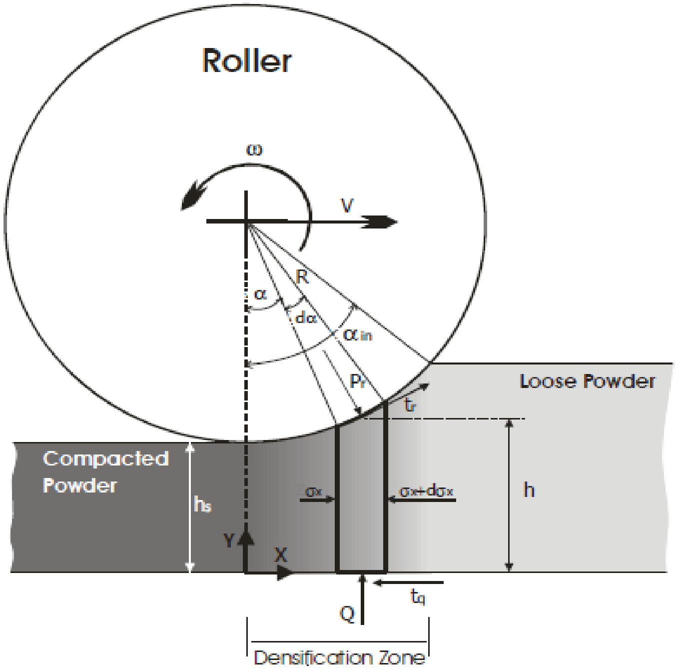


Figure 8 Powder Densification Zone

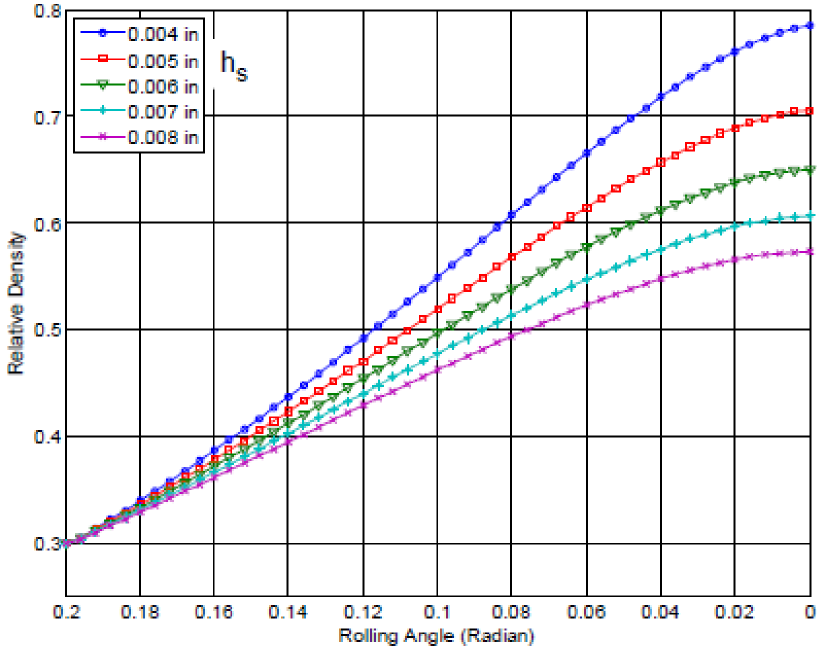


Figure 9 Effect of layer thickness on RD in powder densification zone

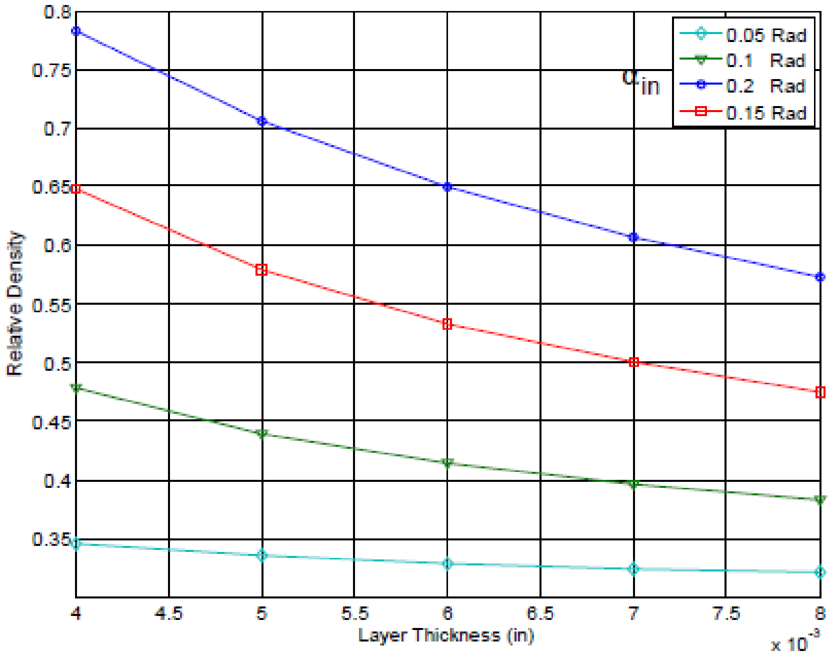


Figure 10 RD of new compacted powder layer with respect to layer thickness

- A small roller diameter and a large new layer height achieves a lower level of compaction as compared to a roller with a larger diameter and smaller layer height.
- Binder selection is of utmost importance in regards to the generation mold with high strength and requisite permeability. The binder system depends on which binder is used, which catalyst is mixed with it, if there is an activator in the sand and the comparative proportion of each. The catalyst needs to be added slowly into the sand and mixed thoroughly before the resin is introduced. The resin and catalyst should never be mixed with each other directly because the highly exothermic reaction could result in an explosion [8].
- Heat curing of the mold also has a direct effect on the sand mold properties. It improves and provides additional strength as compare to uncured molds and in some cases is even necessary to compensate for the poor compaction of the molds as compared to traditional ones. The heating however doesn’t noticeably have any effect on the hardness and surface quality of the printed molds [9].

Considering all of the research that has already been done, there is significant room for further research that still needs to be carried out to develop a better understanding of the properties of parts produced by 3D printing.

CHAPTER 3: METHODOLOGY

Keeping in mind the cost of other additive manufacturing techniques, and just like the commercially available 3D sand printers, a powder bed binder jetting mechanism has been selected for the development of the lab scale setup as a part of this research. The following sections discuss the sequential steps for the design and development.

3.1 Selection of Resin & Print Head

Considering the unavailability of and toxic nature of furan based no bake resins, alkaline phenolic resin and its corresponding catalyst was procured for the research directly from Excel Engineering. The binder and catalyst system have an approximate density of 1.228gm/ml & 1.173gm/ml respectively and present the following advantages:

i. It doesn’t give out toxic or irritating odors
ii. It has excellent shakeout characteristics
iii. Its thermoplastic properties reduces mechanical defects
iv. It has lower sulfur and nitrogen content
v. It provides flexibility in mold handling

After having procured the resins, a relevant print head was selected. The inkjet print head technology was taken into consideration which is primarily classified into the following two categories;

i. **Piezoelectric Print Heads:** Piezoelectric print heads differ from thermal print heads in the sense that opposed to heat energy, very tiny piezoelectric crystals present in the head force the liquid out as they tend to expand when electric charge is applied. The amount of discharged liquid can be controlled with high accuracy by controlling the applied voltage.

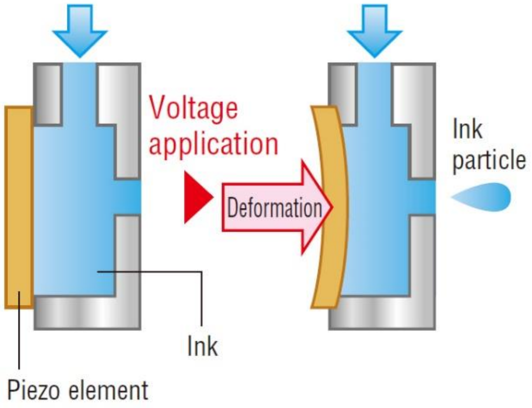


Figure 11 Piezoelectric Print Head Working Mechanism

ii. **Thermal Inkjet Print Heads:**

Thermal print heads use heat energy to heat up the liquid and force it through the nozzles. They are one of the most common inkjet printers seen in common households because they tend to be more affordable. They however tend to burnout if run on dry conditions.

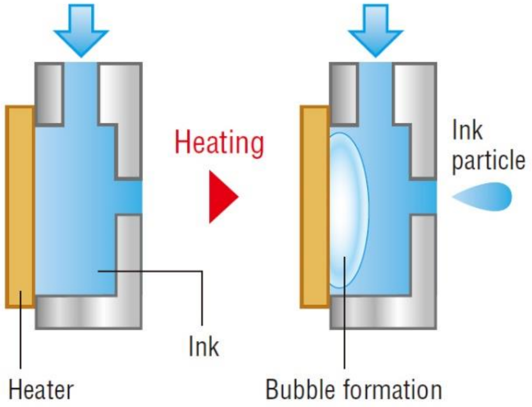


Figure 12 Thermal Print Head Working Mechanism

Taking into consideration the curing characteristic of the phenolic binder and to prevent clogging upon heating, an EPSON Stylus S22 Printer with a piezoelectric head was selected. The printer has the following specifications and was further fitted with a CISS ink supply kit to ensure a continuous supply of resin.

- Minimum Droplet Size – 4 pl
- Ink Technology – DURABrite™ Ultra
- Printing Resolution – 5,760 x 1,440 dp
- Nozzle Configuration – 90 Nozzles black, 29 Nozzles per color
- No. of cartridges – 4

Figure 13 EPSON Stylus S22 Printer

3.2 Initial Testing

Various initial tests were performed to verify the printability of a 3D sand mold having sufficient strength. These tests are discussed below in a sequential manner.

i. To test the printability of the phenolic resin the ink cartridges were filled with a diluted solution of resin and water since the resin has a considerable higher viscosity as compared to ink. Initial tests were performed using a 50:50 by volume ratio. This was subsequently increased and fixed to a 70:30 (resin to water) ratio after successful prints.

ii. Having proven the printability of the resin, cylindrical sand molds test specimens at different resin & catalyst ratios (including a 70:30 resin to water ratio by volume) were produced to determine the conditions that were necessary to produce molds with the sufficient shape & strength. The following table summarizes the results that were obtained.

Table 2 Initial Test Results for Resin / Catalyst Ratios

Sr.	Resin	Catalyst	Compaction	Results
1.	2%	20%	Uncompacted	Failed to retain shape
2.	5%	20%	Scrapped	Retains some shape
3.	15%	20%	Scrapped	Retains shape but is lumpy
4.	3%	20%	Fully Compacted	Retains shape without lumps

The results show that too low a level of resin without any compaction fails to produce a mold that holds up and too high a level with scrapping produces lumping. Some compaction is necessary for making molds through the traditional way by mixing resin / catalyst in the approximately industrially specified ratios. Although the results aren't a 100% valid for 3D printing of sand molds since layer by layer and drop by drop deposition would overcome the problem of lumpiness, they however indicate that sufficient compaction is necessary if we wish to employ the industrially specified resin / catalyst ratios for traditional techniques.

Figure 14 Initial Test Specimens Using Traditional Ramming Method

iii. To check layer by layer sand and resin adhesiveness, a translucent paper was fed into the printer and 1in x 1in resin (resin 70:30 water by volume) squares were printed. Sieved sand premixed with the activator was scrapped onto the newly deposited resin layer and excess sand was removed. The process was repeated up to 8 times for both single and double resin layers which resulted in thin wafer like test specimens (approximately 0.84mm thick). The specimens had exceptional rigidity once the water content had dried.

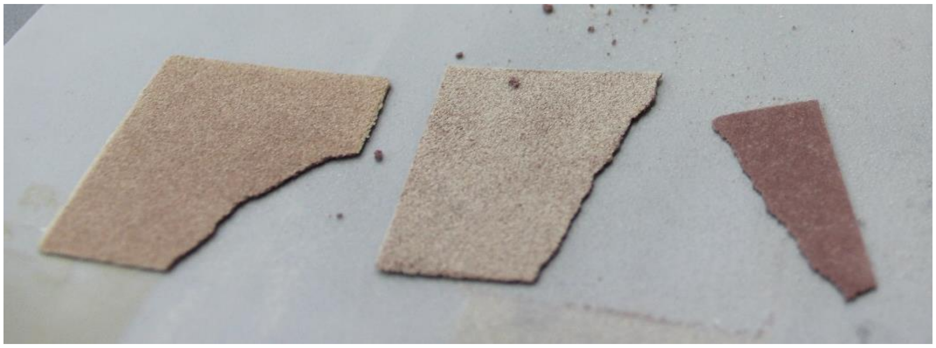


Figure 15 Initial Test Specimens Using Manual Layer by Layer Deposition

iv. To measure the amount of resin printed per square inch by the printer, a pre-weighed absorbent paper is fed into the printer. The paper is weighed again after printing and the change (5.336mg/in^2) gives the weight of resin + water which has been deposited by the print head. Using the respective densities of the two this translates to approximately 3.958 mg/in^2 of resin.

v. From literature it was decided that the setup should be able to deposit sand layers of approximately 100-200 micron thickness. The printable quantity of 3.958 mg resin/in^2 translates to approximately 4.7 – 5.3% resin by weight for uncompacted 100 micron thick sand layer and 3.3 – 3.7% resin by weight for fully compacted 100 micron thick sand layer. Similarly, for 200 micron thickness the values come out to be 2.3-2.7% resin by weight for uncompacted and 1.6-1.9% resin by weight for fully compacted sand layers respectively. The ratios calculated approximately correspond to the industrially specified ratios and ratios used for the initial tests using traditional ramming method. These results along with the thin wafer like test specimens indicate that a single pass resin layer should be sufficient enough to 3D print sand molds with a 100-200 micron thick layer resolution.

vi. Cylindrical test specimens using ratios for a 160 micron thick sand layer from the previous test were constructed (including a 70:30 resin to water ratio by volume) using the traditional method with different compaction levels. These specimens were tested for hardness with a sand mold hardness tester and the corresponding relative density of the specimens was recorded.

Figure 16 Sand Mold Hardness Tester

The results obtained are summarized in the following table.

Table 3 Initial Test Results for Assumed 160 um Layer Thickness

Sr.	Assumed Layer Thickness	Grain Size	Compaction	Hardness	Density (gm/cm$^{3)}$	Relative Density
1.	160 µm	< 150 µm	400 gm	74	1.016	46%
2.	160 µm	< 150 µm	800 gm	82	1.070	49%
3.	160 µm	< 125 µm	400 gm	73	1.024	47%
4.	160 µm	< 125 µm	800 gm	82	1.070	49%

Due to manual making, the results were not accurately reproducible to indicate a trend. The hardness however achieved was greater than the minimum acceptable threshold (~ 65) of the industrial standard. Furthermore, the relative density of the specimens was lower as compared to that of the lose bulk sand (~ 62.7%) which suggest that mold specimens printed with loosely scrapped sand layers should have sufficient hardness. The thin wafer like test specimens printed by manual layer scrapping in the tests conducted before reinforce this suggestion.

3.3 Design & Development of Setup

The design & fabrication phase can be subdivided into four broad sections. These four are discussed below one by one in detail. Majority of the parts are fabricated using a CNC milling machine in order to achieve the required dimensional accuracy.

3.3.1 Support Frame

The complete powder bed platforms and binder jetting mechanism is supported using a support frame which is similar in design to that of a table. The support structure is fabricated using 18 SWG mild steel pipes which hold up the powder bed platforms while the top is made out of a 4ft x 2ft wide acrylic sheet. The complete frame structure measures approximately around 4ft x 2ft x 3ft.

Figure 17 Rendered 3D Model of Support Frame

3.3.2 Powder Bed

The powder bed mechanism consists of two tanks with raising and lowering platforms. These tanks act as the supply bed and the print bed respectively. The print bed size is restricted by the printable area of the selected printer i.e. EPSON Stylus S22 while the supply bed size is half that of the print bed to reduce the layer recoating speed.

The bed platforms move using stepper motors that are coupled with a lead screw. The combination of a 200 step stepper with a lead screw having an 8mm lead provides a resolution of 40 microns per step which is sufficient enough for our purpose. The raising structure also comprise of guide rods and linear bearings for guiding and restricting the movement of the platforms to the z-axis. The complete raising mechanism is fixed to a mild steel base plate which is supported by the support frame.

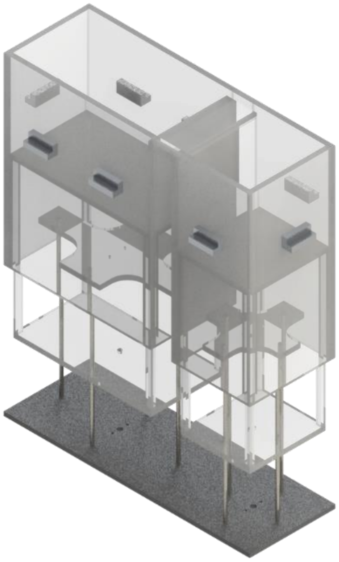


Figure 18 Rendered 3D Model of Powder Bed

The stepper motors are controlled by an Arduino Mega 2560 and a L298N motor driver. The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 while the L298N motor driver is a dual H-Bridge motor driver which allows bidirectional independent control of two DC motors or one bipolar stepper motor [10]. The motor driver acts as a current amplifier. It takes a low current logic control signal from the Arduino Mega 2560 microcontroller and turns it into a higher current signal, using an external power supply, which can drive a motor.

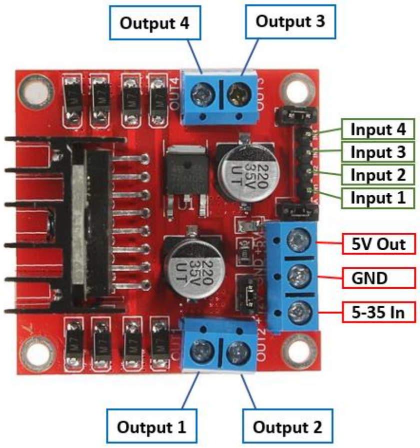


Figure 19 L298N Motor Driver Pinout Diagram

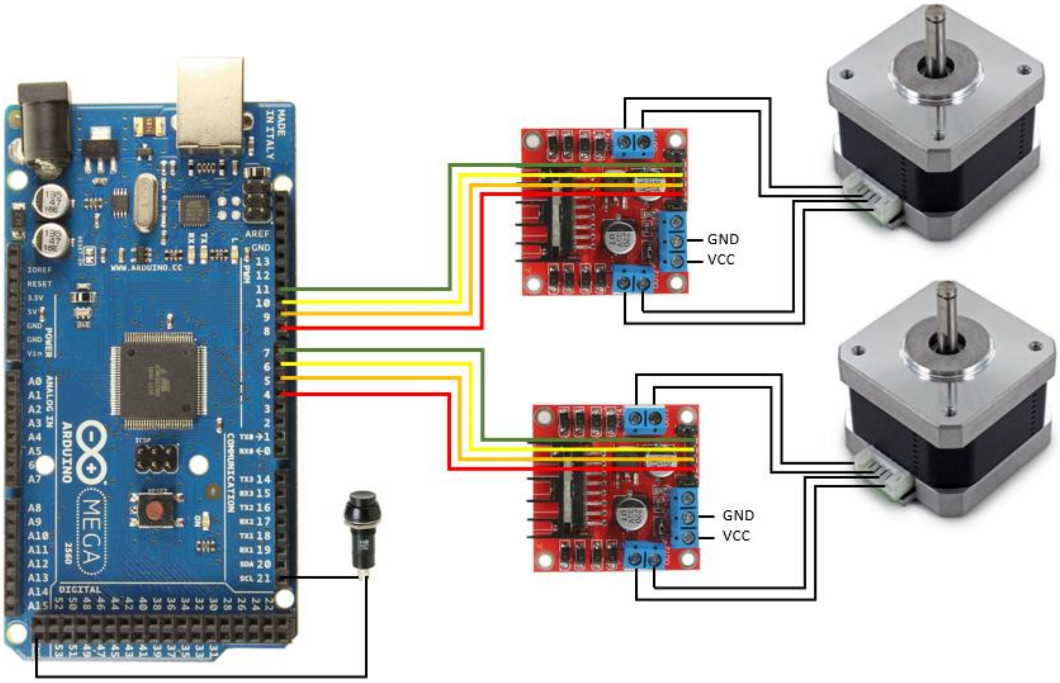


Figure 20 Powder Bed Control Circuit Wiring

3.3.3 Recoater

The recoater mechanism consists of a counter rotating stainless steel roller having a diameter of 16mm. The diameter has been selected taking into consideration the research already conducted by Yaser Shanjani & Ehsan Toyserkani and the effect of an increase in roller diameter on the compaction of the newly deposited powder layer. These studies have already been highlighted under section 2.4 of this report. Furthermore, the counter rotating roller is selected because it creates an even and flat layer as compared to a forward rotating roller which is more prone to disturbing the new powder layer [11].

A timing belt and pulley system is used to feed the roller over the beds and to deposit a new powder layer. Both the rotation of the roller and feed of the rotating roller are controlled by stepper motors whose rpm can be adjusted to optimize the speed and feed of the roller for new layer deposition. Both the stepper motors are controlled by an individual Arduino Mega 2560 microcontroller and a L298N motor driver, the reason being that simultaneous and bidirectional movement of the two motors is required. The Arduino accelstepper library can provide a simultaneous looking movement of two or more than two motors but the movement isn’t ideally speaking simultaneous since the Arduino code is executed in a sequential manner.

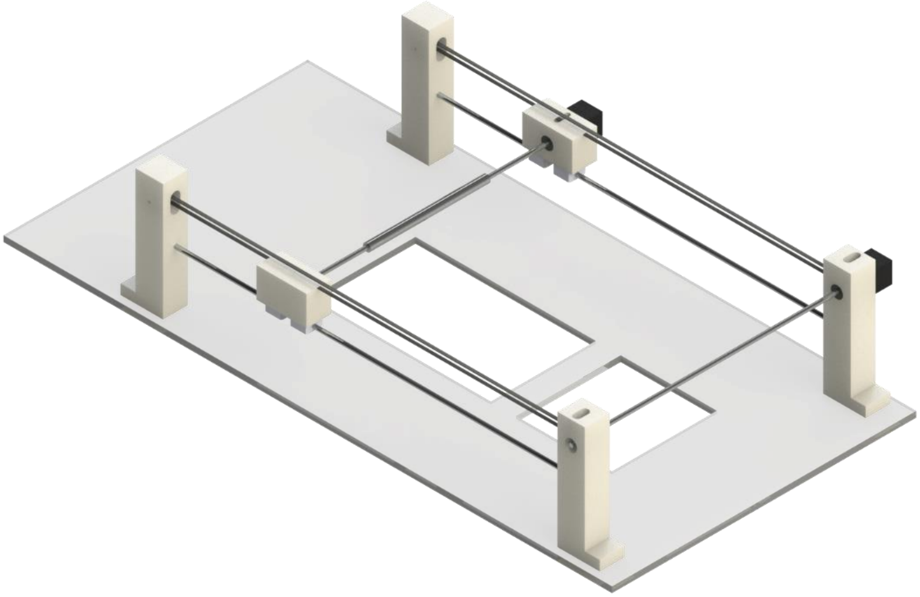


Figure 21 Rendered 3D Model of Recoater

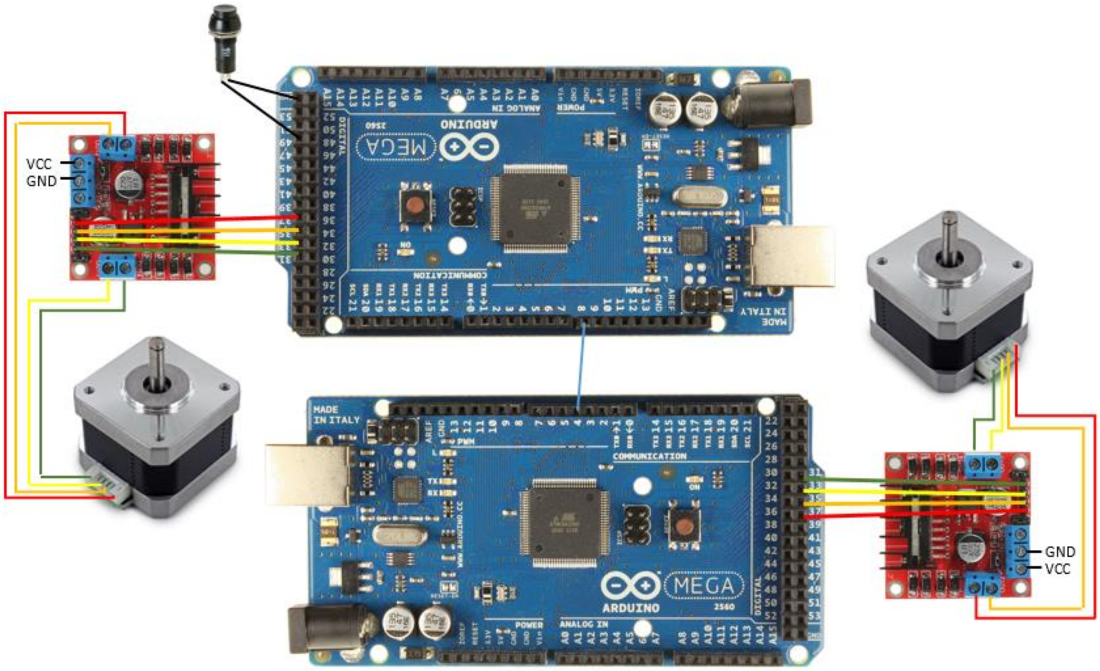


Figure 22 Recoater Control Circuit Wiring

3.3.4 Binder Jetting

An EPSON Stylus S22 printer has been modified for the purpose of this project in such a way that the printer itself moves on the paper instead of feeding the paper (print bed). The redundant components/sensors have been removed or bypassed. Before we move on to which ones to bypass and which ones to remove, we first discuss them and the overall working of the printer in detail.

i. **Paper Tray & Feeder Roller:** The paper tray is where the paper is loaded into the printer and stored. It contains a rubber drum like feed roller which feeds the paper inside during printing. The roller is connected to the paper feed (PF) motor through the PF roller shaft.

ii. **Paper Sensor:** The paper sensor is an optical sensor located after the paper feed roller and before the print area. It checks if the paper has entered the print area and signals the printer if it has or has not. The printer either starts printing or gives us an error depending on this signal.

iii. **PF Encoder:** The paper feed encoder is a dual rotary encoder connected to the PF motor and PF roller shaft. It keeps track of the rotation of the PF motor.

iv. **PF Roller Shaft:** The PF roller shaft connects the PF motor to the pumping cap assembly and the paper feed roller.

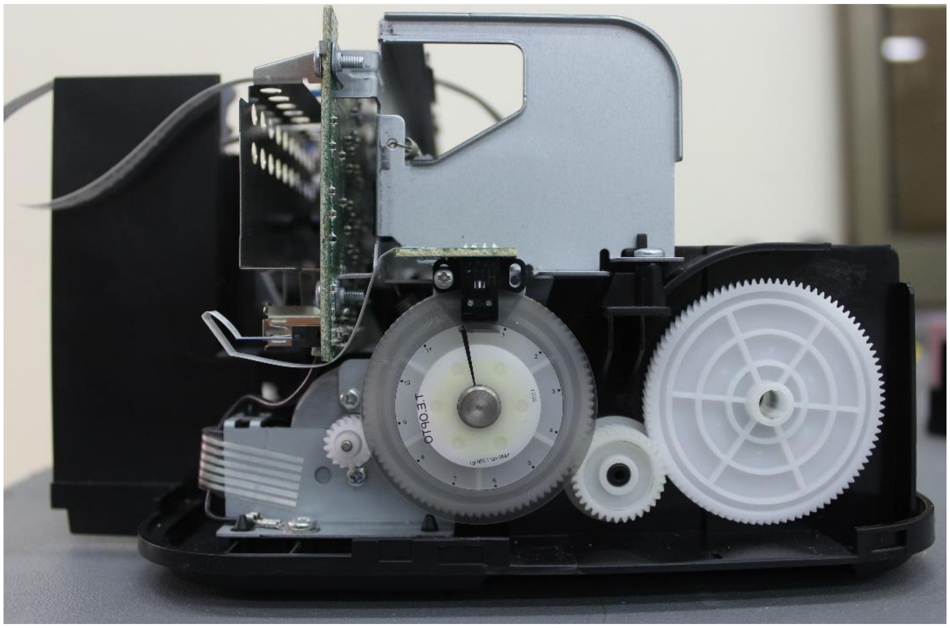


Figure 23 PF Assembly (Motor / Encoder / Roller)

v. **Print Carriage:** The carriage holds the ink cartridges and the print head. It slides on a guide with the help of a timing belt that is connected to a motor. The location and movement is tracked using an encoder strip mounted on the guide and an optical sensor present on the carriage.

vi. **Print Head:** The print head consists of micro piezoelectric elements that squeeze the ink out when an electrical charge is applied.

vii. **Ink Cartridges:** There are 4 ink cartridges that are connected to a CISS (Continuous Ink Supply System) kit. The CISS kit consists of a reset chip and ink tanks that connect to the cartridges through silicon tubes.

viii. **Pump Cap Assembly:** The pump cap assembly is a mechanical pump connected to the PF motor through the PF roller shaft. It is used for pumping and cleaning the print head to prevent clogging of the nozzles. The pumped ink is drained into an ink tank connected to the pump through a small rubber tube.

ix. **Power Supply:** The power supply consists of a main power cord and adaptor which connect to the main circuit board.

x. **Control Circuitry:** It consists of a main circuit board that controls the movement of all the components and decodes the signals received from the sensors and the computer.

xi. **Interface port:** The printer has a USB port to connect to the computer.

The printer performs a head cleaning cycle on startup and lights up the error light if the CISS kit chip needs resetting. Once ready to print and upon receiving a print signal from the computer, the PF motor engages the feed roller through the PF roller shaft and pushes the paper from the tray to the print area. The paper must trigger the paper sensor during a certain time delay on its way to the print area or it will generate an error. If the sensor isn’t triggered it means that the paper is not fed into the tray and if the sensor is already triggered before the feed roller is engaged it means that a paper is jammed inside the print area. If triggered correctly, the printing starts and the paper is continuously fed through the rollers connected to the PF motor until it is completely pushed out and the sensor closes again.

The sequential working of the printer was carefully observed without loading any paper into the paper tray and manually triggering the sensors. This helped to determine which components to remove and which to bypass. Subsequently, the following modifications we made.

- The paper feed roller was removed
- The paper tray was removed.
- The print area was cut out and removed.
- A servo motor was connected to the paper sensor to trigger it through the arduino code.
- The PF roller shaft was cut since it interfered with the powder bed.
- To keep the pumping cap assembly still in operation a syringe was connected for manual pumping.
- The outputs of the dual rotary encoder were tapped which would act as inputs for the feeding mechanism through the Arduino Mega 2560 microcontroller.

The modified printer rests on wheeled mounts that move with the help of DC motors connected to the Arduino Mega 2560 through an L298N motor driver. The mounts are kept aligned using linear bearings and guide rods.

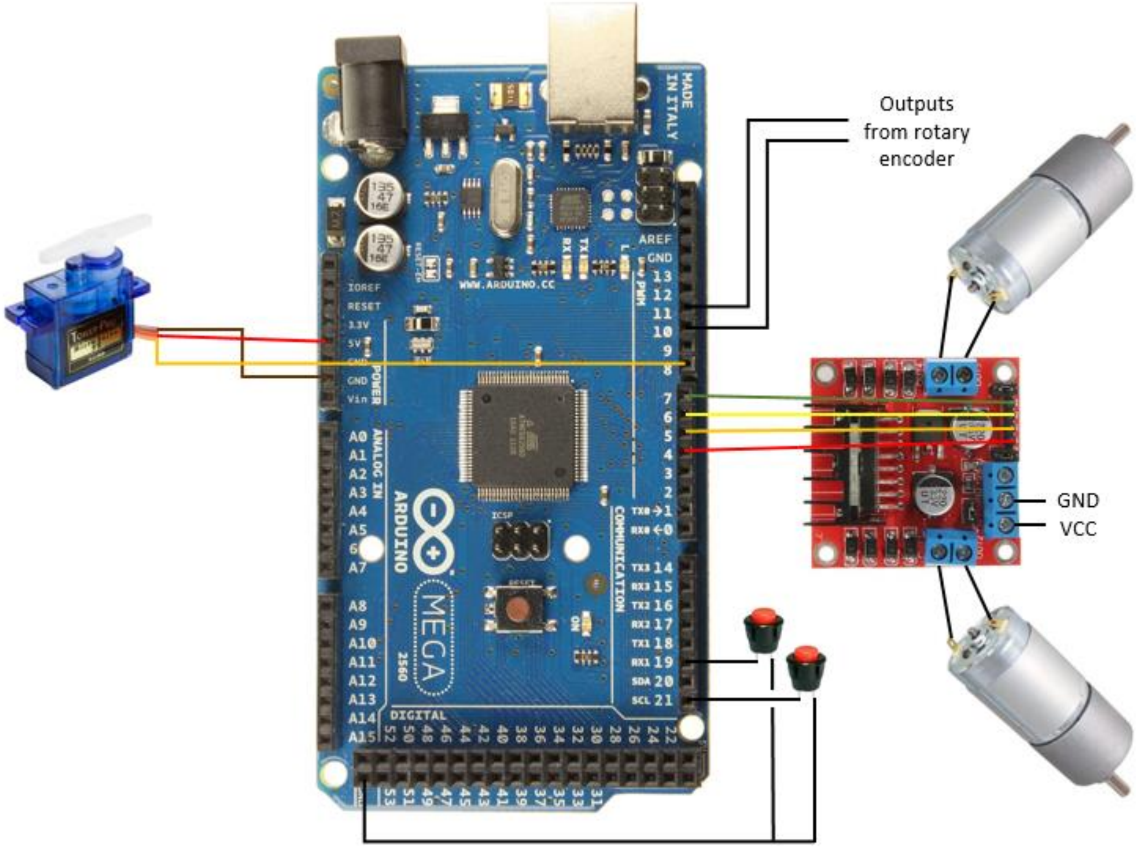


Figure 24 Print Mount Control Circuit Wiring

CHAPTER 4: TESTING & RESULTS

The lab scale setup once fabricated and assembled was ready for testing and calibration. This chapter discusses the operating instructions, the various tests carried out and the outcomes of these tests.

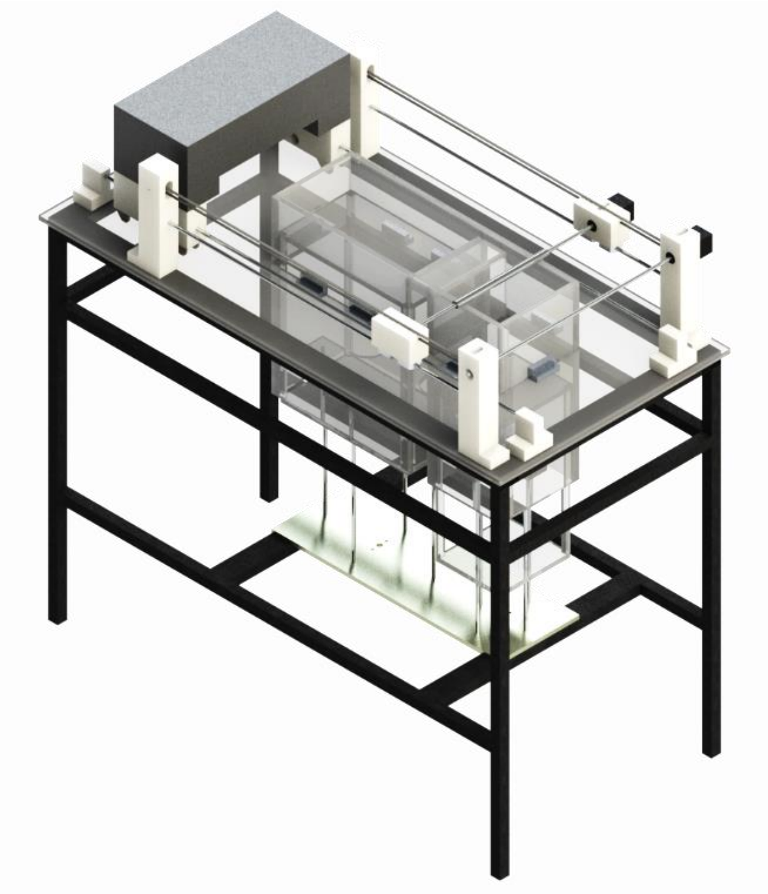


Figure 25 Rendered 3D Model of Final Assembly

4.1 Operating Instructions

The following is a step by step guide to prepare and operate the setup.

i. Fill the CISS tank and cartridges with a resin/water solution having a 70:30 ratio.
ii. Insert the cartridges into the print carriage.
iii. Sieve sand (grain size subjected to desired layered thickness) and mix the catalyst into the sand. Fill the supply tank and the bed of the print tank with this premixed sand.
iv. Connect the power cables to the control panels and the printer.

v. Connect the control panel and the printer to the laptop.
vi. Turn the printer on and manually charge the resin in the print head.
vii. Press the recoat button to smoothen the powder bed.
viii. Place the printer in the printing position and send the print command from the laptop.
ix. Manually trigger the printer using the trigger buttons located on the control panel. Close the trigger once printing is complete.
x. Once the printer returns to its idle position press the platform step button to move the bed platforms.
xi. Press the recoat button to deposit a new sand layer.
xii. Repeat steps viii through xi till a final layer sand layer is deposited.
xiii. Remove the cartridges from the print head and clean them both to prevent clogging of the system.
xiv. Turn the system off and let the part cure for at least 24 hours.
xv. Remove the part from the powder bed and clear off the excess sand.

4.2 Testing & Results

Tests were performed and the system was adjusted accordingly based on the results. The following table summarizes outputs of the various tests performed.

Table 4 Brief Summary of Testing and Results

No.	Parameter	Setting	Result
1	Recoater mechanism	Counter Rotating Roller	The roller while depositing a new sand layer would disturb the previous layer and tend to slide it forward.
	Layer thickness	120 µm	
	No. of resin passes	1 pass	
2	Recoater mechanism	Counter Rotating Roller	The roller doesn’t disturb the previous layers while depositing a new layer however the resin deposited from the print head isn’t sufficient enough to hold the layers together.
	Layer thickness	160 µm	
	No. of resin passes	1 pass	

3	Recoater mechanism	Counter Rotating Roller	The roller while depositing a new sand layer would disturb the previous layer and tend to slide it forward.
	Layer thickness	160 µm	
	No. of resin passes	2 pass	
4	Recoater mechanism	Counter Rotating Roller	The roller while depositing a new sand layer would disturb the previous layer and tend to slide it forward.
	Layer thickness	240 µm	
	No. of resin passes	2 pass	
5	Recoater mechanism	Counter Rotating Roller	The roller while depositing a new sand layer would disturb the previous layer and tend to slide it forward.
	Layer thickness	280 µm	
	No. of resin passes	2 pass	
6	Recoater mechanism	Counter Rotating Roller	The roller doesn't disturb the previous layers while depositing a new layer however the resin deposited from the print head isn't sufficient enough to hold the layers together.
	Layer thickness	320 µm	
	No. of resin passes	2 pass	
7	Recoater mechanism	Scrapper + forward rotating roller	The roller doesn't disturb the previous layers while depositing a new layer since it doesn't provide any compaction however the resin deposited from the print head isn't sufficient enough to hold the layers together.
	Layer thickness	120 µm	
	No. of resin passes	1 pass	
8	Recoater mechanism	Scrapper + forward rotating roller	The roller doesn't disturb the previous layers while depositing a new layer since it doesn't provide any compaction however the resin deposited from the print head isn't sufficient enough to hold the layers together.
	Layer thickness	120 µm	
	No. of resin passes	2 pass	

The recoating mechanism which initially consisted of only a counter rotating roller was modified to a scrapper with a forward rotating roller to be able to deposit new sand layers without disturbing the previous ones. The new mechanism was able to deposit 120 µm layers without disturbing the previous layers for both single pass and double pass resin layers since is provided no compaction. The layers were however still not able to properly stick together providing sufficient strength to the test mold. This outcome contradicts the deduction made earlier that a single pass resin layer should be sufficient enough to 3D print sand molds with a 100-200 micron thick layer resolution. The reason being the presence of granular interlocking which isn't present when a new layer is deposited using a scrapper and roller mechanism with no compaction.

Apart from the layer deposition problem that was resolved another major problem that was encountered was the clogging of the print head nozzles. Even though the solution consisted of 30% water (by volume) the nozzles were ending up clogged. The solution was hence further diluted to contain 40% water (by volume) which still did not resolve the problem. Various chemicals such as acetone, methanol, ethanol, chloroform, IPA etc. were tried to clear the head and to dissolve the cured resin but to no avail.

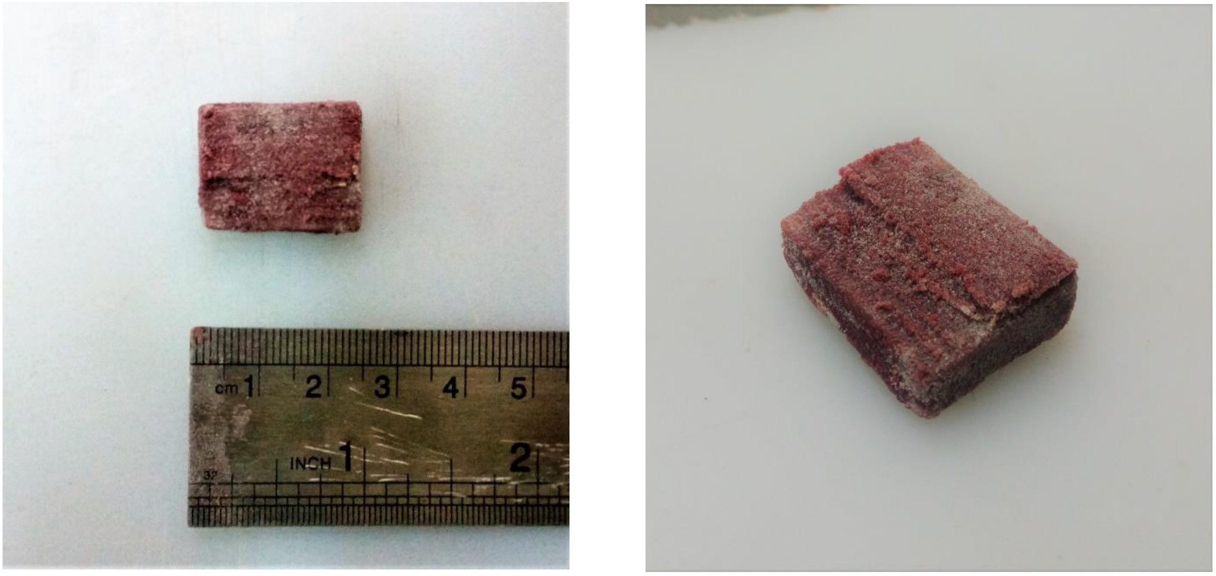


Figure 26 3D Printed Sand Mold Sample

CHAPTER 5: CONCLUSION & FUTURE WORK

The main objective of the research was to develop a 3D sand mold printing setup using layer deposition & drop jet technology that can be furthered researched and worked on. The development of the lab scale setup has been discussed in chapter 3 in detail while the results obtained from the testing of the system have been discussed in chapter 4. This chapter summarizes the outcomes of the research and recommends future work.

Figure 27 Developed 3D Sand Mold Printer Setup

5.1 Conclusion

The objectives that are mentioned in chapter 1 have been successfully achieved step by step. Through the testing that was carried out and has been discussed in chapter 4, it can be concluded that even though the system is able to print a sand mold, a recoater mechanism able to provide compaction without disturbing the previous layers and a print head able to deposit higher quantities of resin is required to print molds having sufficient strength.

5.2 Recommendations for Future work

The setup in its current state isn't able to print sand molds having sufficient strength for casting applications. After carefully concluding the results from the testing of the setup, the limitations of the setup can be worked out in the future with the help of the following suggestions:

i. The size and capacity of both the beds can be increased to print bigger molds.

ii. The curing time can be decreased by heating the bed by installing heaters.

iii. A GUI interface can be made for ease of control.

iv. The scrapper and roller of the recoater mechanism can be adjusted to give a suitable level of compaction, for increasing the mold strength, without disturbing the previous layers. Subsequently the result of compaction on the mold characteristics can be studied.

v. To resolve the head clogging program a piezoelectric print head by Xaar can be used. Xaar is a company that develops world leading piezoelectric drop-on-demand (DOD) inkjet technologies. The TF ink recirculation technology and Hybrid Side – Shooter architecture ensures a continuous fluid flow at a high rate directly past the back of the nozzle which can prevent the resin from curing and subsequently clogging the channels [12]. Furthermore, in some print heads TF Technology can also be set to operate in Pulsed mode – fluid is recirculated when the print head is not jetting.

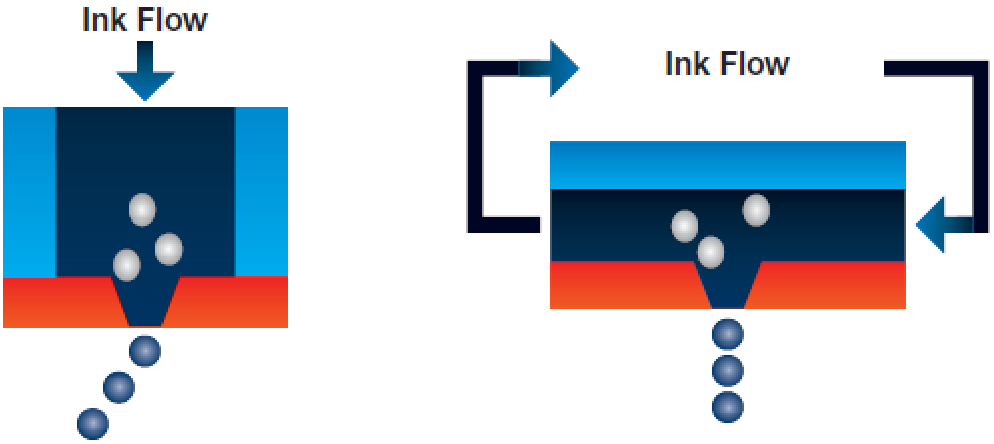


Figure 28 End Shooter VS Xaar's Hybrid Side Shooter Technology

vi. Print heads by Xaar are capable of dispensing millions of droplets per second. The Xaar 1003 family of print heads can repeatedly jet fluids volumes in the range of between 1- 42 pl with an extremely high degree of accuracy. The variable drop print heads can give flexibility in choosing the drop sizes and the relationship between the drop size and 3D printed mold properties can be studied. Furthermore, the relationship between the resin concentration and the mold characteristics can also be studied.

vii. The following components / systems may also need to be purchased for developing the binder jetting system using a Xaar print head;
    - Xaar Midas Ink Supply System
    - Xaar Midas communication pack
    - Inkjet Development System
    - Xaar Head Personality Card
    - Xaar XUSB Drive Electronics
    - Xaar Hydra Ink Supply System
    - Xaar Print Manager (XPM)

viii. Motors with a higher torque may be used to move the bed to ensure that it does do not jam. A feedback loop can also be connected for monitoring.

ix. The setup can be enclosed in a closed container with a proper ventilation system.

APPENDIX A

Code for Arduino # 1

```
#include <Stepper.h>

const int stepsPerRevolution1 = 12;   // supply tank motor

const int stepsPerRevolution2 = 5;    // print tank motor

const int stepsPerRevolution3 = 480;  // roller feed motor

// initializing the stepper library on pins:

Stepper myStepper1(stepsPerRevolution1, 5, 6, 7, 8);

Stepper myStepper2(stepsPerRevolution2, 32, 34, 36, 38);

Stepper myStepper3(stepsPerRevolution3, 9, 10, 11, 12);

void setup()

{

  // setting the motor speed in rpm:

  myStepper1.setSpeed(50);

  myStepper2.setSpeed(50);

  myStepper3.setSpeed(27);

  // initializing the serial port:

  pinMode(19, OUTPUT);

  digitalWrite(19, HIGH);

  pinMode(18, OUTPUT);

  digitalWrite(18, HIGH);

  Serial.begin(9600);
```

```
}
void loop()
{
if (digitalRead(21)==LOW)
  {
  // move platforms one step in forward direction
  myStepper1.step(stepsPerRevolution1);
  myStepper2.step(stepsPerRevolution2);
  }
if (digitalRead(20)==LOW)
  {
  // move platforms one step in reverse direction
  myStepper1.step(-stepsPerRevolution1);
  myStepper2.step(-stepsPerRevolution2);
}
if (digitalRead(19)==LOW)
  {
    digitalWrite(18, LOW);
    delay (10);
    digitalWrite(18, HIGH);
  // start roller feed
  myStepper3.step(-stepsPerRevolution3);
  myStepper3.step(-stepsPerRevolution3);
```

```
  myStepper3.step(-stepsPerRevolution3);

  myStepper3.step(-stepsPerRevolution3);

  myStepper3.step(-stepsPerRevolution3);

  myStepper3.step(-stepsPerRevolution3);

  myStepper3.step(-stepsPerRevolution3);

  delay (150);

  myStepper3.step(stepsPerRevolution3);

  myStepper3.step(stepsPerRevolution3);

  myStepper3.step(stepsPerRevolution3);

  myStepper3.step(stepsPerRevolution3);

  myStepper3.step(stepsPerRevolution3);

  myStepper3.step(stepsPerRevolution3);

  myStepper3.step(stepsPerRevolution3);

  }

}
```

APPENDIX B

Code for Arduino # 2

```
#include <Stepper.h>

#include <Servo.h>

Servo myservo;

int pos = 0;

const int stepsPerRevolution = 500;

// initializing the stepper library on pins

Stepper myStepper(stepsPerRevolution, 4, 5, 6, 7);

void setup()

{

  myservo.attach(8);

  myservo.write(105);

  // set the speed in rpm

  myStepper.setSpeed(12);

  pinMode(19,INPUT_PULLUP);

  pinMode(10, OUTPUT);

  pinMode(12, OUTPUT);

  pinMode(2,INPUT_PULLUP);

}

void loop()

{
```

```
digitalWrite(10 , LOW);

digitalWrite(12 , LOW);

if (digitalRead(2)==LOW)

  {

    for (int i=0; i <= 60; i++)

    {

      digitalWrite(10 , HIGH);

      digitalWrite(12 , HIGH);

      delay (5);

      digitalWrite(10 , LOW);

      digitalWrite(12 , LOW);

      delay (2200);

    }

  }

if (digitalRead(21)==LOW)

  {

    myservo.write(80);

  }

if (digitalRead(20)==LOW)

  {

    myservo.write(105);

  }

if (digitalRead(19)==LOW)
```

```
  {
   // start rotating roller
   myStepper.step(-stepsPerRevolution);
   myStepper.step(-stepsPerRevolution);
   myStepper.step(-stepsPerRevolution);
   delay (1500);
   myStepper.step(stepsPerRevolution);
   myStepper.step(stepsPerRevolution);
   myStepper.step(stepsPerRevolution);
  }
}
```

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