Calibration of a Piezo-Electric Printhead in the Selective Inhibition Sintering (SIS) Process for Fabrication of High Quality Metallic Parts

Payman Torabi*, Matthew Petros*, Behrokh Khoshnevis*

*Daniel J. Epstein Department of Industrial and Systems Engineering, Los Angeles, CA 90089

Abstract

Selective Inhibition Sintering (SIS) is a disruptive Additive Manufacturing process capable of printing parts from polymers, metals and ceramics. In this paper the application of a commercial piezo-electric printhead in SIS-metal is studied. This replaces the single-nozzle solenoid valve previously used in the process and allows the fabrication of high quality metallic parts due to smaller droplet sizes as well as high resolution printing mechanisms. A Design of Experiments (DoE) approach has been utilized to study the effects of important factors in printing the inhibitor. These factors include: composition of the inhibitor, quality of the print, and amount of fluid deposited for each layer. Based on the results of these experiments, parameters have been identified for the creation of highly accurate three-dimensional parts.

Introduction

Additive manufacturing

Additive manufacturing (AM) processes fabricate physical objects directly from 3D models and other digital data sources through a layer by layer manufacturing process. There are many different processes with different methods for the fabrication of each layer of the part, but all share four common steps:

i) The part is first modeled in a CAD software in computer
ii) The 3D model is sliced digitally into different layers with specific thicknesses
iii) The physical part is built layer by layer in the AM process
iv) The part is post-processed to achieve the desired aesthetics and/or mechanical properties

Industrial processes are looking for ways to fabricate parts with higher qualities without sacrificing the production speed. With this end in mind, inkjet technologies present a tremendous opportunity to AM processes due to their high resolution and high speed print abilities. Therefore, integrating inkjet printing into a potential process can vastly increase its capabilities.

Use of inkjet printheads in AM

Inkjet printing involves depositing droplets of ink as small as 10 microns in diameter under precise digital control. There are many different methods for generating and ejecting the droplets out of the print-head nozzles. Most of these methods can be classified into two main categories; continuous inkjet (CIJ) and drop-on-demand (DoD). This classification can be seen in Figure 1. Both methods print liquid through small orifices called nozzles. In CIJ the flow of the liquid is continuous. Conversely, DoD systems are impulsive, meaning small droplets are formed which can be positioned separately as needed [1].

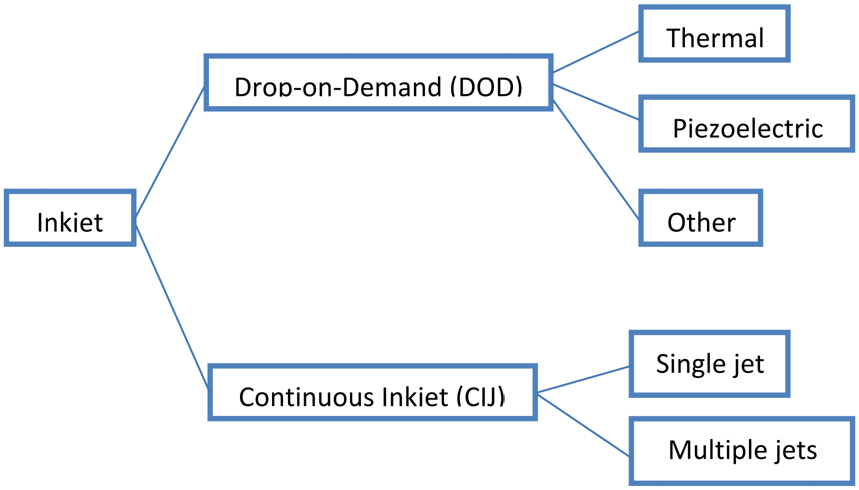


Figure 1: Classification of inkjet technologies [1]

Inkjet technologies can be used to print different types of materials such as metals, ceramics, polymers, and chemical compounds. The only requirement is that the fluid needs to be in liquid form with appropriate rheological properties. This can lead to many different applications of inkjet printing in manufacturing. Figure 2 summarizes possible routes for using this technology in manufacturing.

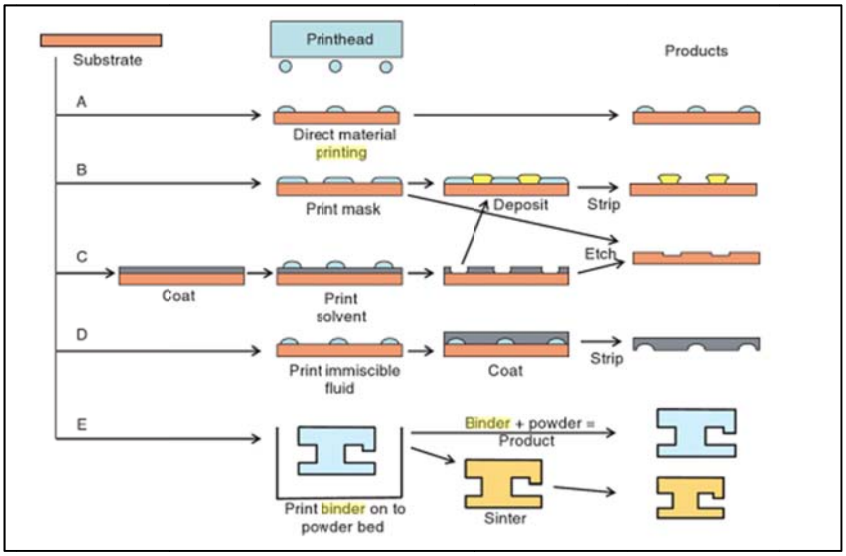
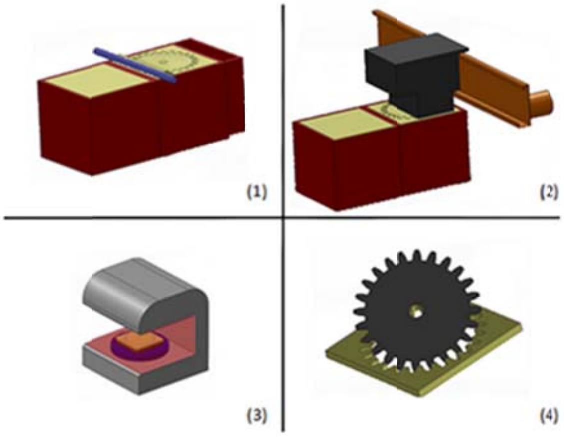


Figure 2: Possible routes by which inkjet printing can be used to create structures [1]

There is also a wide range of applications of inkjet technologies in additive manufacturing [2]. Figure 2E demonstrates Three-Dimensional Printing (3DP) process which uses DOD inkjet technology to print binder onto a powder bed, fabricating the part layer by layer. Although there are numerous other AM processes that use inkjet printing, this paper focuses on the application of a DOD piezoelectric print-head in Selective Inhibition Sintering (SIS).

Selective Inhibition Sintering

SIS is a novel AM process developed by Prof. Behrokh Khoshnevis at the University of Southern California [3]. The core principle behind SIS is inhibiting selected regions of the powder to prevent sintering. For fabricating a metallic part using SIS, a layer of powder is first spread onto the build tank. An inhibitor solution is then deposited onto selected regions of the layer. The inhibitor is only deposited on the boundary of the part without affecting internal regions. The next layer is then spread over the previous one and the inhibitor is deposited again. These steps are repeated until all the layers for the part are completed. The part is then bulk sintered in a furnace under appropriate atmosphere. In this stage, all areas of the part will be sintered except the ones treated by the inhibitor. Finally, the inhibited regions are manually removed, revealing the part. An analogy would be to think of the part as if it were inside a sacrificial mold. The SIS steps are summarized in Figure 3.



***Step 1**: A thin layer of metal powder is spread over the build tank.*

***Step 2**: Liquid inhibitor is deposited along the layer profile with an inkjet print head, and the stage moves down.*

- *Repeat Steps 1, 2 until the entire part has been completed layer by layer.*

***Step 3**: The part is bulk sintered in a conventional sintering oven under appropriate atmosphere.*

***Step 4**: The inhibited regions are removed, revealing the desired part and its negative.*

Figure 3: Steps for part fabrication using SIS

SIS-metal has several advantages over other commercially available metal processes, such as:

- The machine will be much cheaper due to the use of a commercial printhead instead of expensive laser or electron beam generators
- The process is faster since only the boundary of the part needs to be treated whereas in other methods, the whole area inside the part should be scanned or treated [2]
- SIS is far more scalable regarding the size of the printed parts. Bigger parts can be created without any reduction in the resolution of the build
- Since any needed supports are attached to the “sacrificial mold”, and not the part itself, the part surface quality is not affected.

SIS-Metal Alpha Machine

Much research has been conducted on SIS over the last decade resulting in significant progress for the process. This is evidenced by the quality of the printed parts and optimization of important parameters of the SIS process [4, 5]. The SIS-metal machine developed in the current research is the second generation of SIS-metal. In the previous machine developed by

Yoozbashizadeh [6], a single DoD solenoid nozzle with an orifice size of 0.005” (0.127mm) was used for depositing the inhibitor onto powder layers. Due to the lack of control over droplet size and jetting force, the penetration of the droplets into the powder and consequently the layer thickness were relatively large at 800 microns. In Figure 4, the SIS-metal alpha machine (first generation machine) and its respective sample parts are shown. The alpha machine served as proof-of-concept for the process for metals and specifically for the fabrication of bronze parts.

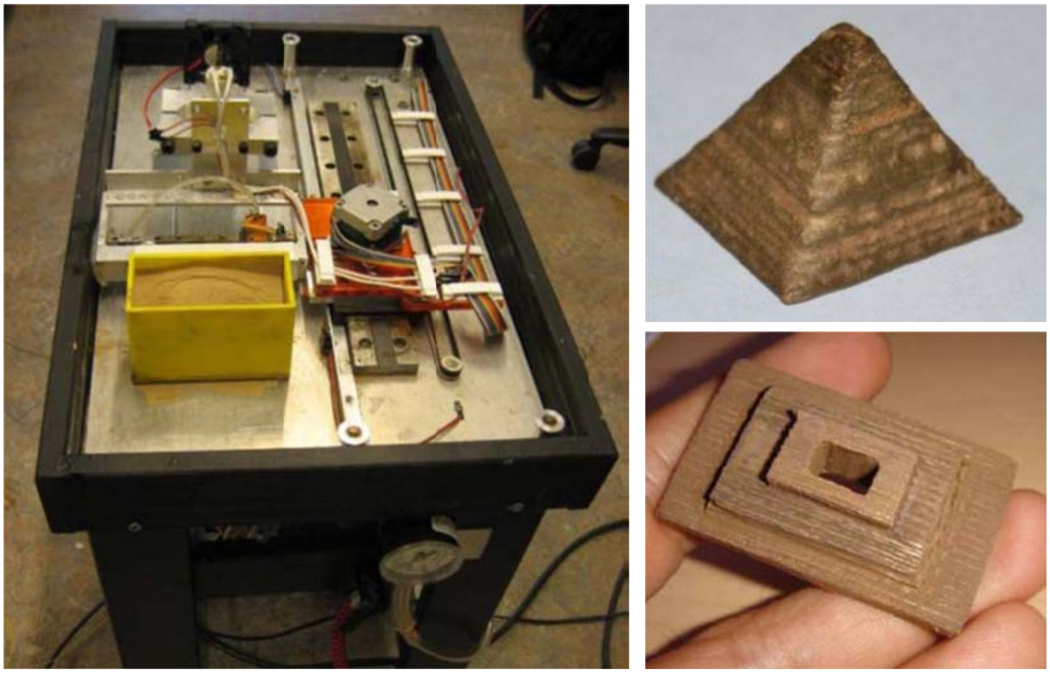


Figure 4: SIS-Metal alpha machine and some sample parts printed using it

SIS-Metal Beta Machine

In order to print high quality parts, having control over droplet sizes deposited on the layers and their corresponding penetration depth onto the powder bed is a necessity. For this purpose the use of a DOD high resolution inkjet printhead is needed. The most affordable options in the market are commercial home-use photo printers which utilize either Thermal or Piezoelectric printheads. In a thermal printhead, a heated resistor evaporates a small portion of the ink forming an air bubble which forces a droplet of ink onto the medium. On the other hand, with a piezoelectric (PZT) head, a signal is sent to the piezo actuators causing them to squeeze and form a droplet by pushing fluid out of an orifice [7]. The greatest advantage that makes PZT printheads the better choice for this research is their higher tolerance for variances in the properties of the fluid being printed such as viscosity, surface tension and density. This makes the calibration of the composition of the fluid easier and enables the use of different candidate materials for inhibition.

The Epson Workforce 30 (WF30), a high resolution and high performance piezoelectric printer [8], was chosen and incorporated into the SIS-metal beta machine. This printhead provides different droplet sizes, resolutions and print qualities that need to be calibrated to meet the SIS process requirements. The calibration of the parameters will be discussed in later sections. The WF30 printhead has three rows of nozzles with each row containing 180 nozzles. Two rows dedicated to black color cartridges and one row is divided into three 60-nozzle sections for the other three color cartridges (Cyan, Magenta and Yellow) [9].

The SIS-metal beta prototype machine consists of a three-axis motion system, a piezoelectric printhead, a controller board, motion control software and user-interface software (Figure 5).

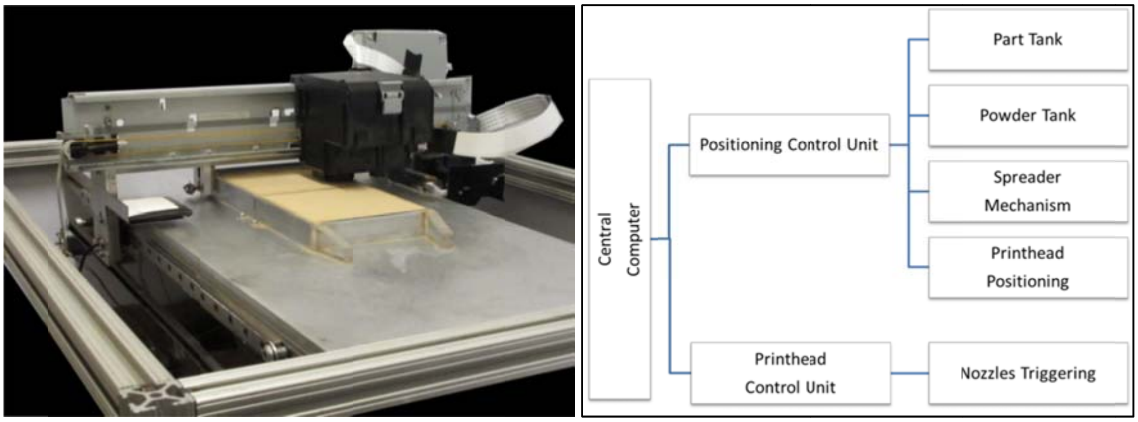


Figure 5: (a) SIS-Metal beta machine (b) Block diagram of the machine

Calibration of the Machine Parameters

There are two sets of parameters that play key roles in the process; the composition of the fluid (inhibitor) and the print settings. The fluid should be fine-tuned such that it is jettable and inhibition still occurs. However, these two properties of the fluid are at odds with each other. For the greatest level of inhibition to occur, the fluid should contain a high level of solute. Unfortunately this increases the viscosity of the fluid which reduces its jettability. Once the fluid is fine-tuned, the print settings are important in calibrating the depth of penetration into the powder bed. Depth of penetration determines the layer thickness, which in turn affects the resolution and surface quality of the finished part.

Inhibitor

The key components of the inhibitor solution are water, sugar, and an industrial surfactant. The concentration of sugar determines the degree of inhibition that can be achieved. The amount of water and surfactant are important in the jettability of the solution as well as penetration of the solution into the powder. As was previously mentioned, there is a trade-off between the degree of inhibition and the jettability and the penetration of the solution. Therefore a series of experiments was conducted to find the optimum composition of the inhibitor solution. The properties of the fluid that play an important role in its jettability are viscosity and surface tension. Previous SIS research provided some candidate solution compositions based on the inhibitors ease of penetration into the powder layer and the degree of inhibition. These solutions were tested for their jettability with the new printhead. For this purpose their viscosities were measured and compared to the viscosity of the original Epson ink. The goal was to choose the solution with a viscosity approximately matching the ink. Figure 6 shows the experimental setup used for determining the viscosities of the inhibitor solutions and the ink.

Figure 6: AR 2000ex viscosity test equipment

The experimental parameters for the rheometer were set at a constant temperature of 24 °C, 1% strain, and a varying frequency that ranged from 1Hz- 35 Hz. The results for the original Epson ink and the chosen inhibitor solution are shown respectively in Table 1 and Table 2.

Table 1: Viscosity test results for magenta ink

Frequency	Viscosity
8Hz	19.3 cP
10Hz	16.6 cP
12Hz	16.2 cP

Table 2: Viscosity test results for inhibitor solution

Frequency	Viscosity
8Hz	11.7 cP
10Hz	12.3 cP
12Hz	12.5 cP

The average viscosity of the inhibitor solution is 12.2 cP and the average viscosity of the Epson ink was 17.4 cP.

Printer Settings

As mentioned earlier, Epson WF30 provides different options for the ink droplet sizes, quality and resolution of the prints, and the number of nozzles engaged in the printing process. These factors along with the number of prints on each layer determine the penetration depth of the inhibitor fluid into the powder, powder surface quality after droplet deposition, and print speed.

Before calibrating the printer settings, the powder layer thickness needed to be adjusted. The metal powder used in this research was a fully alloyed bronze with chemical composition presented in Table 3. The powder particle size has a distribution of 98.7% -325mesh, 1.3% -200/+325mesh as reported by the manufacturer. Thus, the layer thickness cannot theoretically be less than the largest particle size, approximately 80 µm. For calibration of the layer thickness, the current spreading mechanism in the machine was used to spread layers with differing thicknesses. The minimum layer thickness that could be spread consistently was 120 microns. This layer thickness was used in the determining the print settings. It should be noted that the SIS process is applicable to smaller layer thicknesses. The limiting factor in the current study was the particle size.

Table 3: Chemical Composition of the used bronze powder

Copper	90%
Tin	10.00%
Lead	0.025%
Zinc	0.04%
Iron	0.058%
Phosphorous	0.085%

A design of experiments approach was utilized here to investigate the significant and optimum values of the print parameters. The goal was to choose the best combination of factors that gives a depth of penetration of slightly more than 120 microns, an acceptable surface quality, and a satisfactory print speed. Each DoE consisted of a set of small squares printed on a thick layer of loose powder. Each square was printed with a unique combination of the controllable factors. The factors included: printed color which determines the number of nozzles engaged, print quality which determines the droplet sizes, and number of passes which directly affects the penetration depth as well as the surface quality. Three different levels were considered for each factor. The factors and their corresponding levels can be seen in Table 4.

Table 4: Important factors and their levels used in the DOE

		Levels		
Factor	**Description**	**0**	**1**	**2**
1	Color	Cyan	Magenta	Both (Blue)
2	# of Passes	4	7	10
3	Print Quality	Text/Image	Photo	Best Photo

The experimental design is shown in Figure7a. Table 5 shows the print factors for the first 5 squares of the experiment. After printing the squares with their assigned factors, they were bulk sintered in the furnace. The inhibited powder in the printed areas was then removed (Figure7b). As can be seen in the figure, the final part consists of small squares with different depths of penetration. By measuring the depth of each square and visually comparing the surface qualities, the settings that give the most penetration depths as well as the best surface qualities were determined. The experiment was repeated a three times to ensure repeatability.

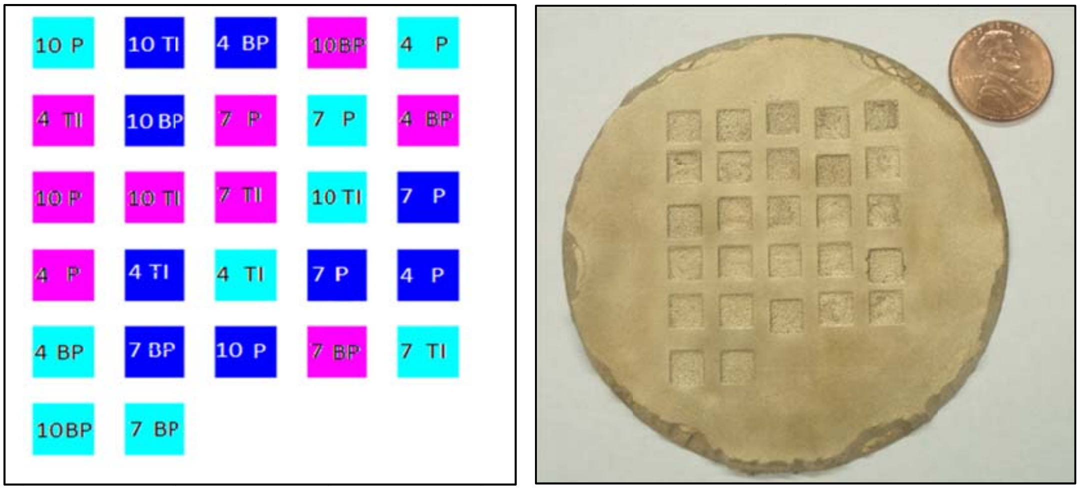


Figure 7:(a) Experimental design (b) The printed part

Table 5: Factor combinations for the first 5 squares

Square No.	**Color**	**No. of Prints**	**Print Quality**
1	Cyan (C)	10	Photo (p)
2	Blue (B)	10	Text/Image (TI)
3	Blue (B)	4	Best Photo (BP)
4	Magenta (M)	10	Best Photo (BP)
5	Cyan (C)	4	Photo (P)

Based on these experiments, it was observed that printing with both colors simultaneously (which equals to an RGB value of R0, G0, and B255) gives the greatest depth of penetration. This results in a faster printing process due to less passes required for each layer. Figure 8 illustrates the penetration depth vs. number of prints for printing with both colors under different print qualities. As shown in the figure, four prints with both colors provide a depth of penetration slightly over 120 microns as desired. To choose among the print qualities other factors such as speed and surface quality are also considered. Table 6 summarizes the comparison between different print qualities. Based on the table, photo quality is set as the print quality of the machine.

Table 6: Comparison of different print qualities

Factors\print qualities	**Text/Image**	**Photo**	**Best Photo**
Speed	High	Med	Low
Surface quality	Low	High	High
Penetration depth	Low	High	Med

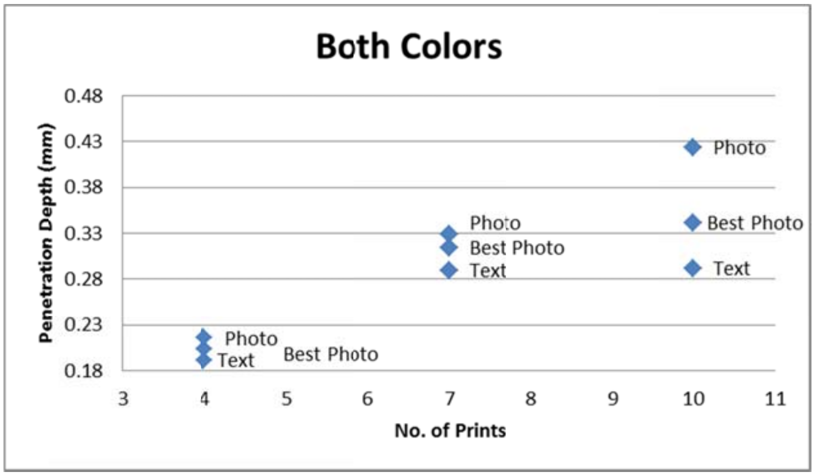


Figure 8: Penetration depth vs. no. of prints for both colors with different print qualities

Minimum feature experiment

Once the optimum parameters for the solution and the printer were determined, parts were fabricated in order to test different features of the machine, such as the minimum wall thickness, minimum hole dimensions and minimum gap sizes.

Figure 9 illustrates the design part fabricated to test the resolution of the machine. On the top, there are square holes with different dimensions which show the smallest hole that can be inhibited. On the left several lines with different thicknesses are printed that determine the smallest gap size. Finally, the shapes on the right demonstrate the minimum wall thickness that can be printed with this machine under the defined parameters.

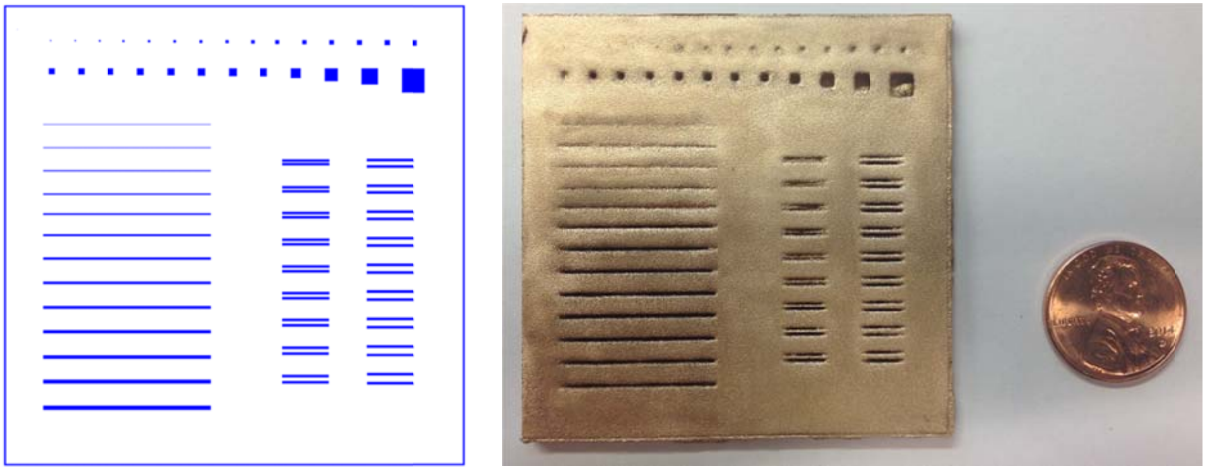


Figure 9: Fabricated part for testing the resolution of the machine

The results of the measured features are demonstrated in Table 7.

Table 7: Feature size measurements

Feature	Measurements (microns)
Gap size	330
Square Hole Side	820
Wall Thickness	250

Conclusion

In this research an additive manufacturing machine was designed and manufactured that utilizes a high resolution piezo-electric printhead. The developed SIS-metal beta machine demonstrates the high potentials of the SIS process in the additive manufacturing field. The preliminary experiments are also carried out with the machine to test and verify its capability in additive manufacturing of metallic parts. Figure 10 represents some basic parts fabricated with SIS-metal beta machine.

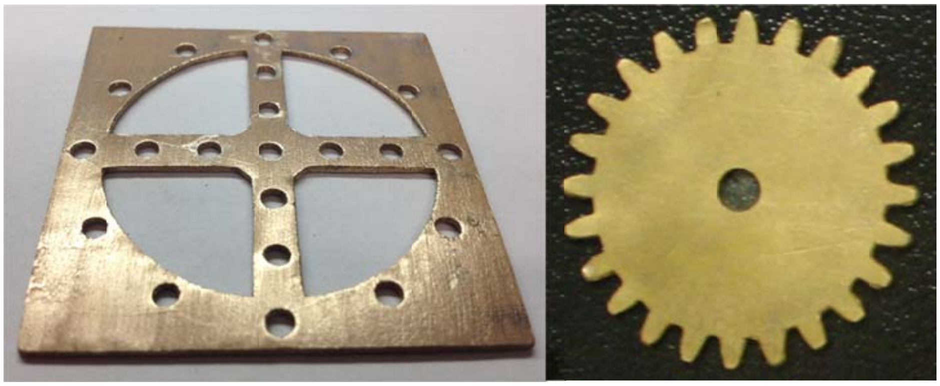


Figure 10: Basic shapes fabricated with the SIS-metal process

Future Research

The future researches will be concentrated on the robustness of the machine, improving the mechanical properties of the part such as their strength and porosity, studying the shrinkage and surface quality of the parts, and developing slicing software that can handle complicated 3d shapes and generate layer slices specifically for the SIS process.

References

[1] Hutchings, Ian M., and Graham D. Martin, eds. *Inkjet technology for digital fabrication*. John Wiley & Sons, 2012.

[2] Gibson, Ian, David W. Rosen, and Brent Stucker. *Additive manufacturing technologies*. New York: Springer, 2010.

[3] Khoshnevis, Behrokh, et al. "SIS–a new SFF method based on powder sintering." *Rapid Prototyping Journal* 9.1 (2003): 30-36.

[4] Asiabanpour, Bahram, et al. "Advancements in the SIS process." *Proceedings from the 14th SFF Symposium, Austin, Texas*. 2003.

[5] Behrokh Khoshnevis, Mahdi Yoozbashizadeh, Yong Chen, (2012) "Metallic part fabrication using selective inhibition sintering (SIS)", Rapid Prototyping Journal, Vol. 18 Iss: 2, pp.144 – 153

[6] Yoozbashizadeh, Mahdi. *Metallic part fabrication with selective inhibition sintering (SIS) based on microscopic mechanical inhibition*. University of Southern California, 2012.

[7] Ink Jet Printers Technical Brief. (2007, May 1). *Epson*

[8] Epson Micro Piezo Print Head Technology. (2010, January 1). *Epson Exceed Your Vision*.

[9] Kwan, Joyce G. *Design of electronics for a high-resolution, multi-material, and modular 3D printer*. Diss. Massachusetts Institute of Technology, 2013.