











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  $\mu\text{m}$ . 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**

Factor	Description	Levels		
		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.

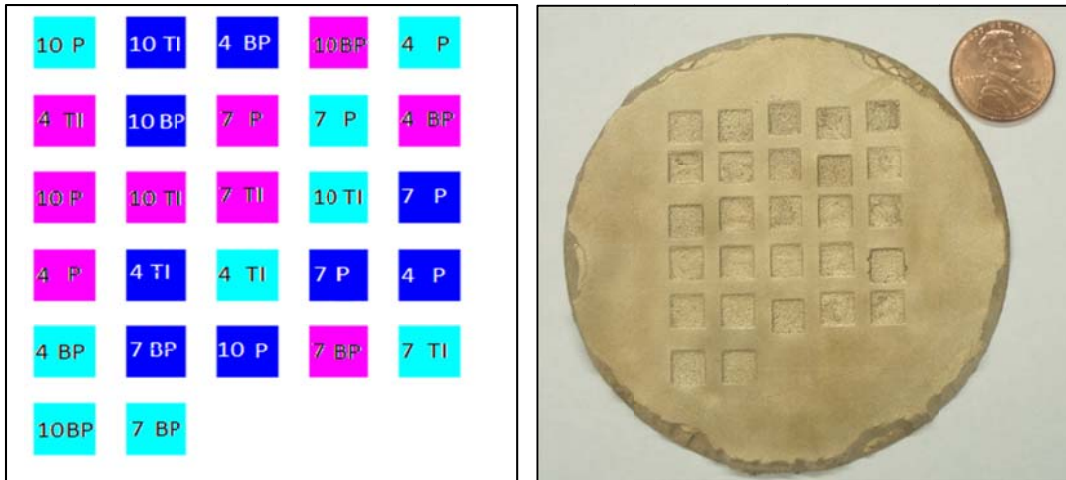


Figure 7:(a) Experimental design (b) The printed part

Table 5: Factor combinations for the first 5 squares

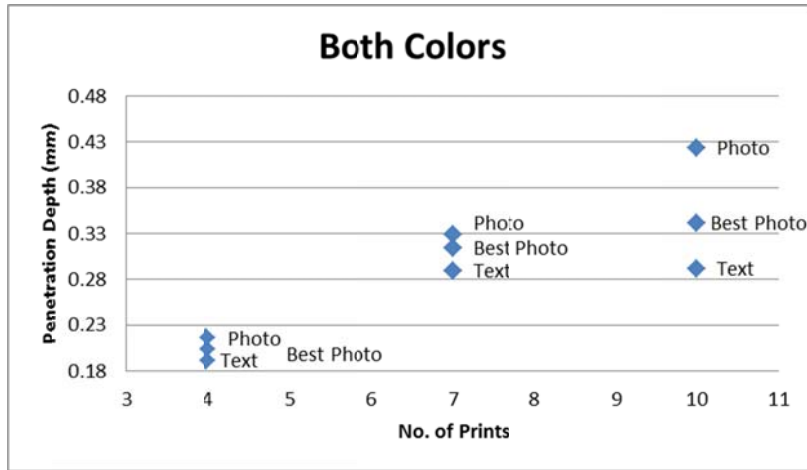
Square No.	Color	No. of Prints	Print Quality
1	Cyan (C)	10	Photo (p)
2	Blue (B)	10	Text/Image (TI)
3	Blue (B)	4	Best Photo (BP)
4	Magenta (M)	10	Best Photo (BP)
5	Cyan (C)	4	Photo (P)

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



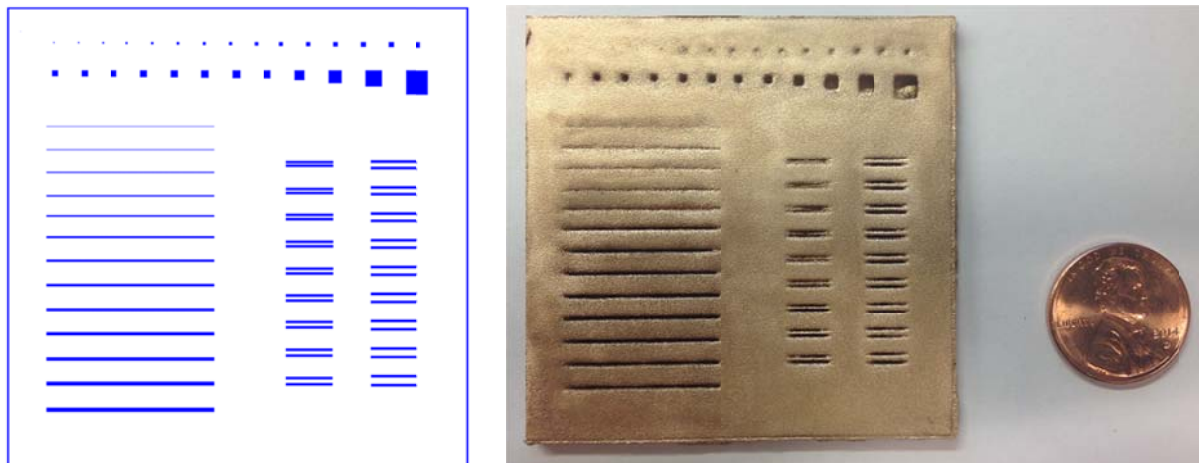


**Figure 8: Penetration depth vs. no. of prints for both colors with different print qualities**

### 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**

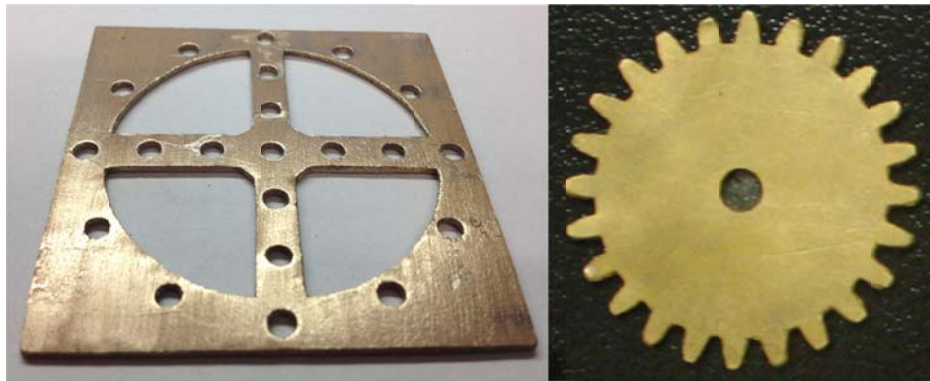
The results of the measured features are demonstrated in Table 7.

**Table 7: Feature size measurements**

<b>Feature</b>	<b>Measurements (microns)</b>
<b>Gap size</b>	330
<b>Square Hole Side</b>	820
<b>Wall Thickness</b>	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.

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