

# Investigation of Key Parameters for Syringe-printing of Nano-silver Paste

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## Abstract

Additive manufacturing (AM) techniques, also known as 3D printing, have been embedded into electronic components used for power modules as they can meet complex design requirements with less material waste and shorter lead-time. However, the corresponding manufactural considerations need to be investigated to ensure good printing quality. This paper is a parametric study of previous research [1], specifically focusing on the key parameters for the syringe-printing method that has been used to print a single-layer planar transformer winding implemented on a 10kW DC-DC power converter. A series of key parameters such as kick, trim length, feed rate, and pass spacing are defined, followed by inquiring into the printable regarding the width of a single trace and the gap/printing spacing between two traces. The results indicate that the targeted trace width and gap are subjected to certain errors, resulting in an imprecise actual print, that cannot be employed when designing a CAD model. Instead, a set of recommended values corresponding to the targeted values are acquired. Linear relations between the actual values and targeted values are obtained, which provides convenience for further design when considering using syringe-printing as an AM technique to print nano-silver traces. Keywords – Additive manufacturing, electronic component, planar transformer windings, syringe-printing, nano-silver

## 1 Introduction

In power electronics, there is a trend utilizing AM technologies to fabricate electronic components, such as planar inductors, planar transformers, and conductive traces, for advanced power modules, which typically require a reduced package size in which a complex circuit design to ensure electrical performance and a corresponded thermal management to dissipate heat generated by the main electronic components are required. For such an advanced power package, there is a pressing need for the manufacturing team to explore the manufactural considerations when using AM as an implementation. In the recent 5 years, the most commonly used AM techniques in fabricating electronic components are ink-jet-based and paste-based systems. Ink-based AM system can be classified into inkjet printing (IJP) and aerosol jet printing (AJP), both enabling non-contact deposition of various materials, such as nano-silver particle inks. IJP has been used to print transistors and integrated circuits [2] [3] [4] [5] [6]. Its key parameters for IJP are the velocity of the fluid, the density of the ink materials, the dimension of printed length, the dynamic viscosity, the surface tension, and the minimum velocity for an ejected drop. The corresponding relations are given by [6] and [7].

$$N_{Re} = \frac{v\rho a}{\eta} \quad (1.)$$

$$N_{We} = \frac{v^2\rho a}{\gamma} \quad (2.)$$

$$Oh = \frac{\sqrt{N_{We}}}{N_{Re}} = \frac{\eta}{\sqrt{\gamma\rho a}} \quad (3.)$$

$$v_{min} = \left(\frac{4\gamma}{\rho d_n}\right)^{\frac{1}{2}} \quad (4.)$$

Where,  $N_{Re}$  is Reynolds number,  $N_{We}$  is Weber number,  $Oh$  is Ohnesorge number,  $v$  is the velocity of the fluid,  $\rho$  is the density of the ink material,  $a$  is the dimension of printed length,  $\eta$  is the dynamic viscosity,  $d_n$  is the nozzle diameter, and  $\gamma$  is the surface tension.

AJP has the ability to print multilayer ceramic capacitors [8], sensors [9] [10], and transistors [11]. The key parameters are survival probability, tube length, tube radius, the terminal settling velocity, and the average flow velocity. The relations have been summarized by [12]

$$F = \frac{2}{\pi}(\alpha\beta + \sin^{-1}\beta - 2\alpha^3\beta) \quad (5.)$$

$$\alpha = \left(\frac{3Lu_{TS}}{8u_a R}\right)^{\frac{1}{3}} \quad (6.)$$

$$\beta = \sqrt{1 - \alpha^2} \quad (7.)$$

Where,  $F$ ,  $L$ ,  $R$ ,  $u_{TS}$ , and  $u_a$  are the survival probability, tube length, tube radius, the terminal settling velocity, and the average flow velocity, respectively.

The paste-based system is a type of extrusion technique, and it has been demonstrated primarily in the field of planar magnetics [1][13] [14] [15] [16]. Unlike ink-based system, the key parameters for the paste-based system have not been studied explicitly as they are varied from printers. There are mainly two types of printers based on the movement of the nozzle. One has a movable nozzle that can travel in the X-Y plane while the build-plate moves in the Z direction. The other one has a nozzle shifting in all the X, Y, and Z directions while the base plate is

motionless. However, regardless of the types of the paste printer, the printing speed, piston's pressure, nozzle's inner diameters, and distance between the nozzle's tip and the build-plate are the main considerations in terms of printing quality. This paper defines the above parameters based on the printer used to conduct research in [1].

## 2 Equipment and materials

### 2.1 Equipment

A paste printer, VOLTERA V-One, purchased from VOLTERA, Inc., is shown in Fig. 1 and used to conduct this research. Thanks to the pressurized extruder installed with a cartridge which can be pre-loaded with feed materials, the paste can be syringe-printed on the build-plate with a dimension of 135 mm x 113.5 mm under a controllable speed. During the printing, the build-plate is fixed while the extruder is moving in X, Y, and Z directions.



**Figure 1.** VOLTERA V-ONE printer used in this research

### 2.2 Materials

The material used in this study is nano-silver pastes purchased from NBE Tech, LLC, which has a relatively low theoretical electrical resistivity and a good thermal conductivity, making it a proper candidate for windings material. Table 1 lists all the datasheets.

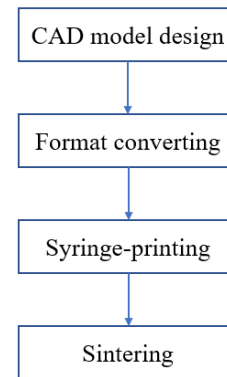
**Table 1.** Datasheet of the nano-silver paste purchased from NBE Tech, LLC

| Parameters of nano-silver paste | Approx.                      |
|---------------------------------|------------------------------|
| Porosity                        | <30%                         |
| Density                         | >7.9 g/cm <sup>3</sup>       |
| Viscosity                       | ~300,000 cps                 |
| CTE                             | 19.6 x 10 <sup>-6</sup> /°C  |
| Melting temperature             | 961°C                        |
| Sintering temperature           | 250°C                        |
| Elastic modulus                 | 10 to 30 GPa                 |
| Electrical resistivity          | <2.6 x 10 <sup>-6</sup> Ω·cm |
| Thermal conductivity            | >200 W/m·K                   |

## 3 Parametric study

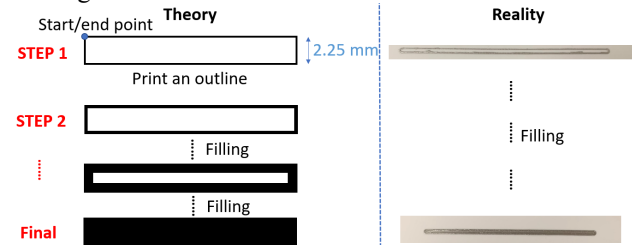
### 3.1 Defining key parameters for deposition

Fig. 2 exhibits the flowchart of the process using syringe-printing for manufacturing windings, in which a parametric study is needed to be performed in the part of syringe-printing to ensure a precise print as it is predesigned in CAD software.



**Figure 2.** Printing methodology of syringe-printing for manufacturing windings

Fig. 3 illustrates the operational principle of the V-one printer. Once the CAD model is transferred into the printer, the extruder's motor first drives the nozzle with a specific inner diameter to print an outline of the geometry and then starts a filling process until the entire object is fully filled. The printer decides the number of fillings based on the pass spacing, the minimum center-to-center distance between two printed adjacent lines. Take a segment with a width of 2.25 mm for instance, the printer firstly extrudes a rectangle outline and then fills in the blanks.



**Figure 3.** Illustration of V-one printer's operational principle in terms of theoretical and real cases.

The key parameters for deposition targeted to be investigated are as follows:

- Kick – discrete application of pressure to printing cartridge
- Trim length – maximum print length for a single kick
- Feed rate – the speed at which the extruder nozzle moves
- Pass spacing – the minimum center-to-center distance between two printed adjacent lines
- Nozzle height – distance between the nozzle and the substrate

There is a balancing between the kick and trim length as the adequate extrusion of paste relies on a ratio between kick and trim length, and the ratio varies depending on the

viscosity of the paste. A high trim length requires a high kick. However, it is taking the risk of cartridge rupture when a higher kick value is set. A low kick can prevent rupture, but it produces a low trim length, resulting in a time consuming to get the entire geometry printed and yielding a rougher print. After investigating, the best value for the kick and trim length are 0.35 and 40 mm when using nano-silver paste as a feed material.

Another balancing exists between feed rate and pass spacing. The feed rate is controlled to maximize printing quality. A high feed rate can yield gaps in a trace intended to be continuous as the materials do not have enough time to lay down the substrate. Oppositely, a low feed rate can lead to thicker prints that may get into trouble with clogging. The pass spacing is dictated by the feed rate and inner diameter of the nozzle installed on the cartridge. The selection of the nozzle is hinged on the particle size in pastes. The general rule of thumb is that the nozzle's inner diameter should be 6x larger than the particles proposed to be dispensed to avoid clogging. The pass spacing is typically supposed to allow for proper overlap of printed lines without letting the nozzle contact the deposited paste. To explore the balancing between feed rate and pass spacing, a controlling of variable method is used. Select a nozzle with an inner diameter of 225 microns and set the feed rate to be 500 mm/min, and modulate the pass spacing to acquire the minimum allowable pass spacing between two traces without running into a shorting issue.

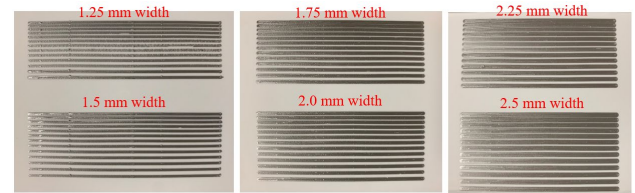
Nozzle height is less concerned with other parameters. A proper value should leave enough space for paste extruding but keep the nozzle tip from immersing in the depositing paste, further destroying the deposited paste.

### 3.2 Printing region

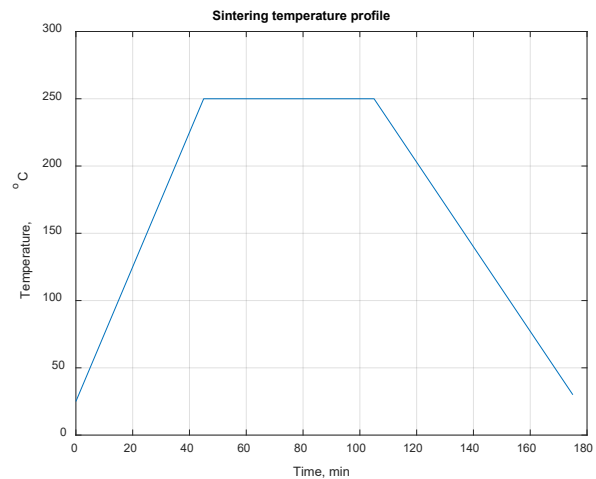
Table 2 specifies the range of the width of the printed traces and the gap between the two traces. Based on the typical design of transformer windings, the range of the width of each trace was selected between 1.25 mm, 1.5 mm, 1.75 mm, 2.0 mm, 2.25 mm, and 2.5 mm, while the spacing between the two traces was set between 0.25 mm, 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm, 0.8 mm, 0.9 mm, and 1.0 mm. In total, 66 segments were planned for the test. A constant feed rate of 500 mm/min and a nozzle with an inner diameter of 250 microns was used. It is worth mentioning that the spacing is the gap between two segments filled out with nano-silver paste, as elaborated in Fig. 3. Fig. 4 shows all the syringe-printed segments at room temperature as straight lines with different widths and gaps on an alumina base plate, followed by a brief sintering profile obtained from the datasheet and shown in Fig. 5 to examine possible shorting via 2-probe tests. Symbol X means the two traces under the corresponding settings touch each other. Shorting becomes a failure mode. For example, when the width of each trace is selected to be 1.25 to 2.25 mm, a spacing of 0.25 mm is unreachable as the two traces will contact, resulting in shorting. Symbol O indicates the sample survived (i.e., no contact between the two traces).

**Table 2.** The range of the printable width of a straight trace and the range of the gap between two straight traces

| Width (mm) | Spacing (mm) |     |     |     |     |     |     |     |     |     |     |
|------------|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|            | 0.25         | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| 1.25       | X            | O   | O   | O   | O   | O   | O   | O   | O   | O   | O   |
| 1.5        | X            | O   | O   | O   | O   | O   | O   | O   | O   | O   | O   |
| 1.75       | X            | O   | O   | O   | O   | O   | O   | O   | O   | O   | O   |
| 2          | X            | O   | O   | O   | O   | O   | O   | O   | O   | O   | O   |
| 2.25       | X            | O   | O   | O   | O   | O   | O   | O   | O   | O   | O   |
| 2.5        | X            | O   | O   | O   | O   | O   | O   | O   | O   | O   | O   |



**Figure 4.** Syringe-printed traces with width of 1.25 mm, 1.5 mm, 1.75 mm, 2.0 mm, 2.25 mm, and 2.5 mm, with spacing ranging from 0.1 to 1.0 mm for each group on alumina substrate after applying a special sintering process obtained from the nano-silver paste



**Figure 5.** Sintering temperature profile of the nano-silver paste

### 3.3 Printed width error

Table 3 summarizes the targeted width, and the actual mean value of width measured 10 times under a microscope. The width, the corresponding standard deviation, and the width difference were calculated by equations (8) - (10), respectively.

**Table 3.** Targeted trace width, mean width, printing errors, and recommended width

| Targeted width (mm) | Mean actual value (mm) | Error (%) | Standard deviation (SD) | Width difference (WD, mm) | Recommended width (mm) |
|---------------------|------------------------|-----------|-------------------------|---------------------------|------------------------|
| 1.25                | 1.1469                 | 8.25      | 0.0407                  | 0.1031                    | 1.1469                 |
| 1.75                | 1.7206                 | 1.68      | 0.0186                  | 0.0294                    | 1.7206                 |

|      |            |      |        |        |        |
|------|------------|------|--------|--------|--------|
| 2.25 | 2.236<br>3 | 0.61 | 0.0356 | 0.0137 | 2.2363 |
|------|------------|------|--------|--------|--------|

$$Error = \frac{|targeted\ width - mean\ actual\ width|}{targeted\ width} \quad (8.)$$

$$SD = \sqrt{\frac{\sum(actual\ width - mean\ width)^2}{measured\ times}} \quad (9.)$$

$$WD = |targeted\ width - mean\ actual\ width| \quad (10.)$$

Then the recommended widths corresponding to the targeted widths were updated. For example, if one intends to print a trace with a width of 1.25 mm, the designed width is recommended to be 1.1469 mm in the CAD software. Fig. 6 reveals that the printing error reduced significantly with increased targeted width. It is recommended to consider a larger width from a manufacturing perspective. However, this may be subject to an electrical design when considering an actual application. Fig. 7 shows a linear relation between actual mean width and targeted width. The linear equation was described by equation (11).

$$Y_{width} = 1.0894X_{width} - 0.2052 \quad (11.)$$

Where,  $X_{width}$  and  $Y_{width}$  represent the targeted width and actual width, respectively.

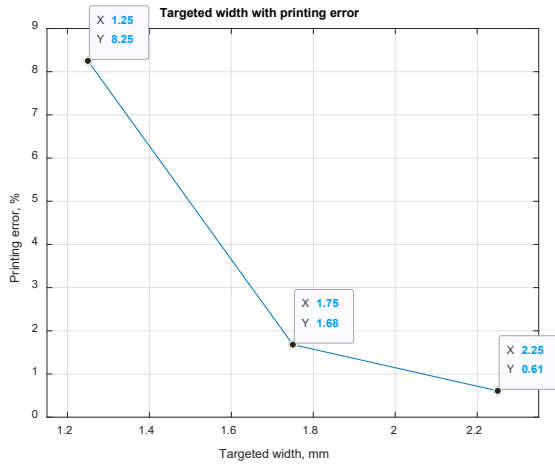


Figure 6. Targeted width VS. width error

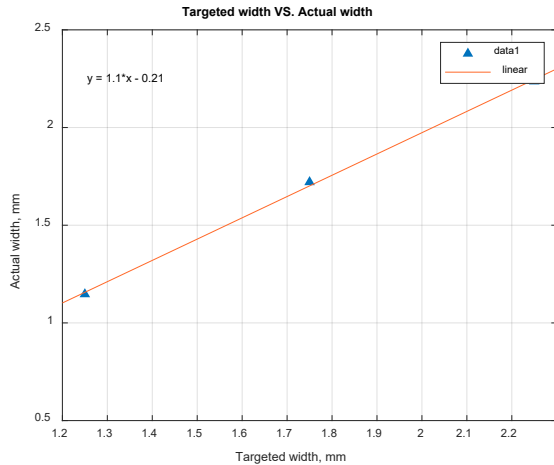


Figure 7. Targeted width VS. actual width

### 3.4 Printed spacing error

Table 4 summarizes the targeted spacing between two printed traces with a width of 2.25 mm, and the mean value of actual spacing measured 10 times under a microscope. The spacing error, the corresponding standard deviation, and the spaces difference were calculated by equations (12) - (14), respectively.

Table 4. Targeted trace width, mean width, printing errors, and recommended width

| Targeted spacing (mm) | Actual mean (mm) | Standard deviation (SD) | Width difference (WD, mm) | Recommended spacing (mm) |
|-----------------------|------------------|-------------------------|---------------------------|--------------------------|
| 0.1                   | 0.1322           | 0.0049                  | 0.0322                    | 0.0678                   |
| 0.2                   | 0.2584           | 0.0043                  | 0.0584                    | 0.1416                   |
| 0.3                   | 0.3638           | 0.0046                  | 0.0638                    | 0.2362                   |
| 0.4                   | 0.4665           | 0.0057                  | 0.0665                    | 0.3335                   |
| 0.5                   | 0.5465           | 0.0050                  | 0.0465                    | 0.4535                   |
| 0.6                   | 0.6191           | 0.0064                  | 0.0191                    | 0.5809                   |
| 0.7                   | 0.7056           | 0.0029                  | 0.0056                    | 0.6944                   |
| 0.8                   | 0.8026           | 0.0023                  | 0.0026                    | 0.7974                   |
| 0.9                   | 0.9094           | 0.0059                  | 0.0094                    | 0.8906                   |
| 1.0                   | 1.0181           | 0.0134                  | 0.0181                    | 0.9819                   |

$$Error = \frac{|targeted\ space - mean\ actual\ space|}{targeted\ space} \times 100\% \quad (12.)$$

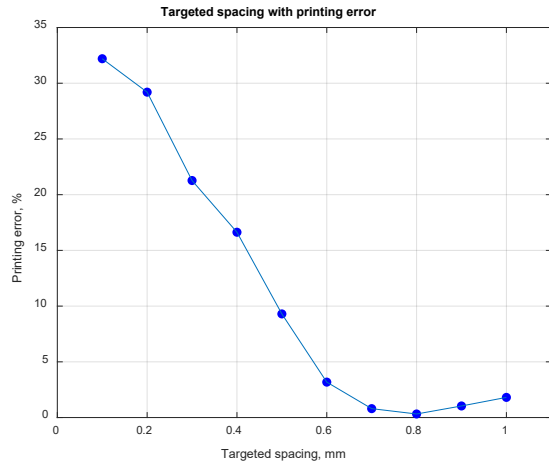
$$SD = \sqrt{\frac{\sum(actual\ space - mean\ space)^2}{measured\ times}} \quad (13.)$$

$$WD = |targeted\ space - mean\ actual\ space| \quad (14.)$$

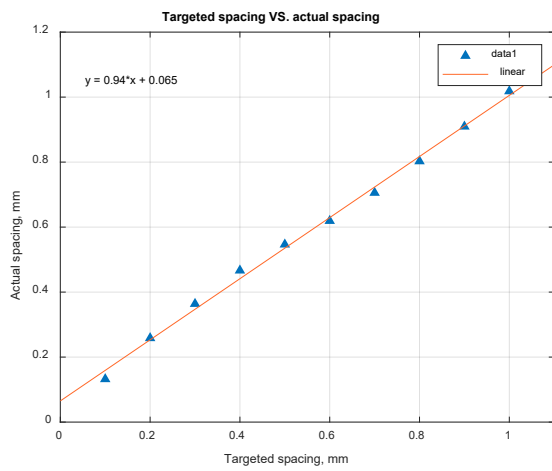
Similarly, the targeted spacings were replaced with the recommended spacings as inputs values. For instance, if 0.1 mm is the targeted gap between two printed traces with a width of 2.25 mm for each, it is recommended to leave a 0.0678 mm spacing in the CAD model. Fig. 8 illustrates that the spacing error can be effectively lowered as the targeted space increases before reaching a threshold spacing value of 0.8 mm. Once the spacing value is more significant than 0.8 mm, the error increases slightly. This reveals a comfortable zone of the spacing for this printer in terms of manufacturing ability, from 0.6 mm to 0.8 mm. However, this should always be coordinated with electrical performance for an authentic design, as a larger gap often generates a higher loss. Fig. 9 elucidates a linear relation between actual mean space and targeted space. The linear equation was expressed by equation (15).

$$Y_{space} = 0.955X_{space} + 0.0591 \quad (15.)$$

Where,  $X_{space}$  and  $Y_{space}$  represent the targeted space and actual space, respectively.



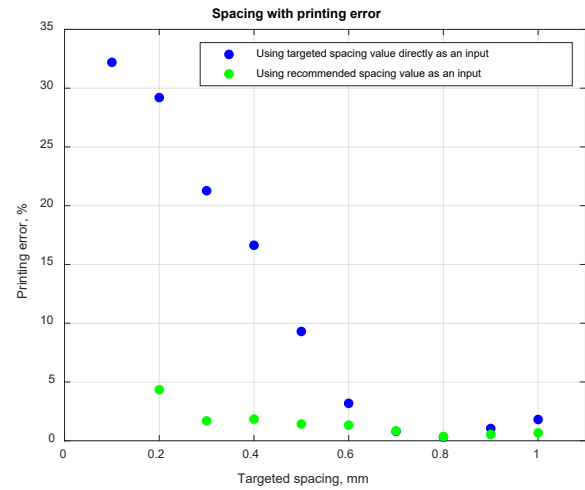
**Figure 8.** Targeted spacing VS. space error



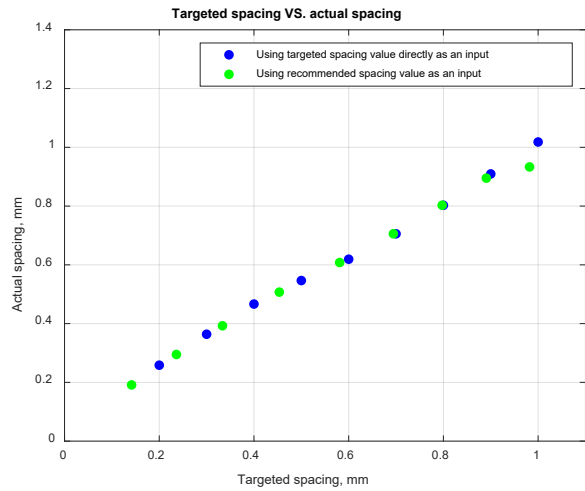
**Figure 9.** Targeted spacing VS. actual spacing

### 3.5 Printed spacing using recommended values

To print an actual spacing closing to the targeted spacing, the recommended spacing obtained in the previous section was taken as an input. Fig. 10 compares the errors before and after applying the recommended spacing values. At a given value of targeted spacing smaller than 0.6 mm, the printing error using recommended values is significantly smaller than those directly using targeted values. When the targeted spacing is set to be 0.6 mm or greater, the printing error results from two inputs are approximately the same as it already reaches the printer's accuracy. In Fig. 11, the relations between targeted and actual spacing for both inputs are plotted and fitted. The linear relations for using recommended values have a slope of 1.0024 closer to 1 compared to the slope of 0.955 using targeted values directly.



**Figure 10.** Comparison of printing error using targeted spacing value directly as an input and using recommended spacing value as an input



**Figure 11.** Comparison of actual spacing using targeted spacing value directly as an input and using recommended spacing value as an input

## 4 Conclusion and future work

This paper defined the critical parameters for a typical paste printer. It also investigated the printable region regarding the width of a trace and the printing error, the spacing error using targeted values (width and spacing) when directly applying the targeted values as inputs, and the actual values when employing the recommended values as inputs. The results revealed that a confident spacing should be set from 0.45 mm to 0.65 mm during the co-design for planar transformer windings between the manufacturing and electrical team. The linear relations between actual value and targeted values in terms of width and spacing were obtained, which can provide convenience for future windings' design. These studies can be considered a reference when using the paste printer whose extruder is movable in all X, Y, and Z directions. However, it may not be suitable for any paste printer involving pressure, which can be one of the potential future works.

## 5 Acknowledgements

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## 6 Literature

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