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Effect of Fabrication Parameters on Surface Roughness of FDM Parts

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The FDM (Fused Deposition Modeling) technology is widely used due to its low process cost and good mechanical properties. However, fabricated parts have relatively inferior surface roughness compared to liquid material type process such as SL (Stereolithography). In this research, effects of fabrication parameters such as the gap between nozzle and substrate, inflow speed of filament material and heating moving speed of nozzle on the FDM-fabricated line figuration was investigated experimentally. The extruded line figurations such as width, thickness and cross-sectional shapes were examined. An empirical formula of the line fabrication for fabrication parameters was made based on the experimental results. Moreover, effect of line fabrication distance on the surface roughness was studied.

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1. Introduction

Additive manufacturing (or 3D printing) technology is classified according to its material type or process. Material type is classified as solid, liquid and powder.[1] Among solid material type additive manufacturing processes, the FDM (Fused Deposition Modeling) process is widely used due to its low process cost and good mechanical properties. However, fabricated parts have relatively inferior surface roughness compared to liquid material type process such as Stereolithography (SL).

A multi-material Additive manufacturing technology is being focused as next-generation Additive manufacturing technology.[2-5] Especially, 3-dimensional circuit device fabrication (3DCD) technology based on additive manufacturing and liquid material dispensing is expected for manufacturing an electronic device without PCB. In 3DCD technology, the 3D printed part takes roles as structure of an electronic device as well as electrical insulation material. Mainly two additive manufacturing processes, SL and FDM, were used for the 3DCD technology.[6-9]

The surface roughness is adequate to dispense liquid conductive material for circuits in the SL-based 3DCD technology. However, this technology requires expensive equipment and a complex process. The FDM-based 3DCD technology, on the other hand, requires relatively inexpensive equipment and a simple process. But its surface roughness is improper as a substrate for liquid conductive material dispensing.

The staircase at the vertical plane is mainly influence on the surface roughness due to the layer-by-layer manufacturing of fabrication system. Moreover, in FDM system, the layer thickness could not be small (less then tens of micrometers) because the diameter of extruded filament material has hundreds of micrometers. Hence the staircase at the vertical surface is remarkable. In this regards, various studies on the vertical surface rough improvement for the FDM process were reported.[10-17] However, compare to other additive manufacturing processes, the surface roughness at the layer surface (normal to the layering direction) of FDM fabricated part is relatively high, too. But there were little studies which focused on the surface roughness at layer surface.

In this research, effects of fabrication parameters such as the gap between nozzle and substrate, inflow speed of filament material and moving speed of heating nozzle on the FDM-fabricated line figuration was investigated experimentally. The extruded line figurations such as width, thickness and cross-sectional shapes were examined. An empirical formula of the line fabrication for fabrication parameters was made based on the experimental results. Moreover, effect of line fabrication distance on the surface roughness was studied, too.

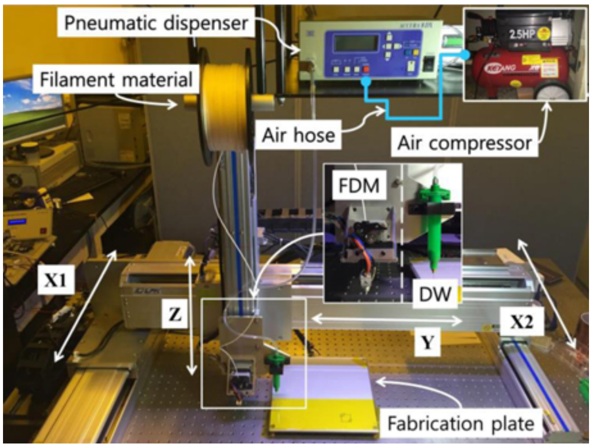

Fig. 1 FDM-based multi-material additive manufacturing system

2. Experimental Setups

The FDM-based multi-material additive manufacturing system was developed to examine whether the fabrication parameters has an effect on the surface roughness of the fabricated structure as shown in Fig. 1. Liquid material dispensing system was also included as well as an FDM extrusion system for the multi-material additive manufacturing system. The aim of our research is to fabricate the 3-dimensional circuit device based on the additive manufacturing technology. In this regards we integrate the FDM head for the fabrication of the structure and dispensing head for the fabrication of conductive lines. The brief conductive line fabrication result is discussed at the end of this paper. Further research on the 3-dimensional circuit device fabrication will be preceded by our group. The head which attached on the z-axis was composed of FDM head and liquid material dispensing head. The z-axis state was attached on the x-y stage system. The stages, FDM head and direct writing head were controlled by PC. X1, X2 and Y axis stages were connected to SGDV-5R5A05A (Yaskawa Co.) motion controller and Z axis stage was connected to MR-J3-10A (Mitsubish Co,) motion controller. Each motion controllers received control signals from the control board (LX504, Comizoa Co.) which was installed in the PC. All the motions were programmed by G-code.

The FDM head (TPC Mechatronics Co., Fig. 2(a)) consisted of stepping motor and nozzle. Control commends for FDM head such as stepping motor speed, nozzle temperature as well as heating bed temperature from the PC were sent to an Arduino Mega 2560 board (Stark Robotics Co.). Then the FDM control board (Ramps 1.4, Big Tree Tech. Co.) which is an open source control board received signals from Arduino Mega 2560 board and generated control voltages for the FDM head and heating bed. Moreover, temperatures of the heating bed and FDM head were controlled by a Ramp 1.4 board which detects temperatures through thermistors.

The dispensing head was controlled by pneumatic dispenser (Accura8-DX, Iwashita Engineering Inc.) which received control signals from control board (LX-504). The pneumatic dispenser controls air pressure from air compressor (KAC-25, Keyang Electronic Machinery Co.). The air pressure sent to barrel through silicone tube (AA10n, Iwashita Engineering Inc.). Nozzle was attached at the end of

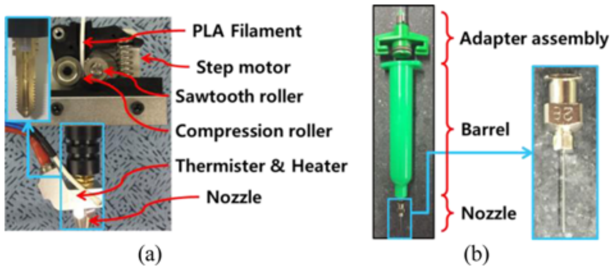

Fig. 2 Photograph of FDM head (a) and dispensing head (b)

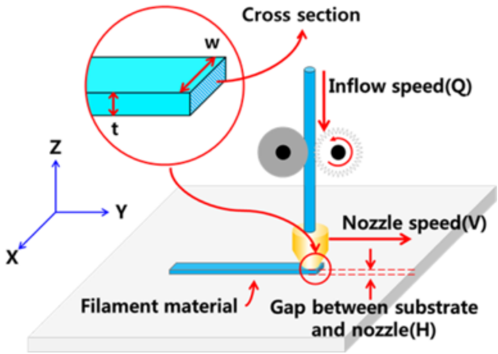

Fig. 3 Line fabrication conditions in a FDM process

barrel. Therefore, liquid material could be dispensed through the nozzle. Fig. 2(b) is a photograph of the dispensing head.

3. Line Fabrication Characteristics of FDM System

3.1 Gap between nozzle and substrate

In the FDM process, the molten polymer material which is extruded through FDM nozzle is pressed between the substrate and nozzle tip. As shown in Fig. 3, the extruded-and-pressed material is cooled and solid line of width (w) and thickness (t) is fabricated. Moreover, surface is fabricated by placing the extruded-and-pressed lines with certain spacing. Therefore, the cross-sectional shape of a line effects on the roughness of a surface. In this regards, it is essential that to examine the line fabrication characteristics for the fabrication conditions. We assumed that the inflow speed of the filament material (Q), moving speed of the nozzle (V) and gap between the substrate and nozzle (H) are major fabrication conditions which affect the extruded line width (w) and thickness (t).

The gap between the substrate and the nozzle (H) and the fabricated line thickness (t) can't be identical. It is because, if the gap between the substrate and nozzle is very small, the extruded polymer material is compressed between the nozzle and substrate and expanded when the nozzle passes by. In this regards, experiments were conducted to examine the thickness and width as well as the cross-sectional shape according to the varying gap between the substrate and the nozzle.

The moving speed of the nozzle and the inflow speed of the filament material were set as 750 mm/min and 200 mm/min, respectively. The temperature of nozzle and substrate were 230°C and 65°C, respectively. The diameter of PLA filament was 1.75 mm (White, TPC Mechatronics).

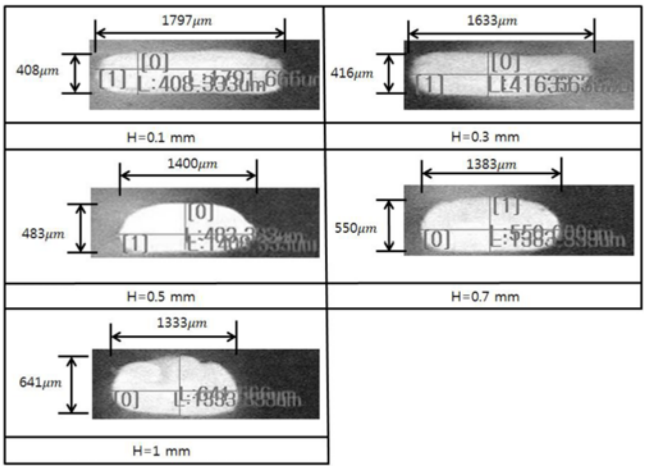

Fig. 4 Photographs of cross-sectional image of a line observed by optical microscope

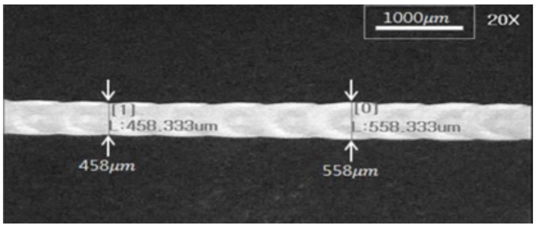

Fig. 5 Microscopic image of line width at gap between nozzle and substrate of 0.05 mm

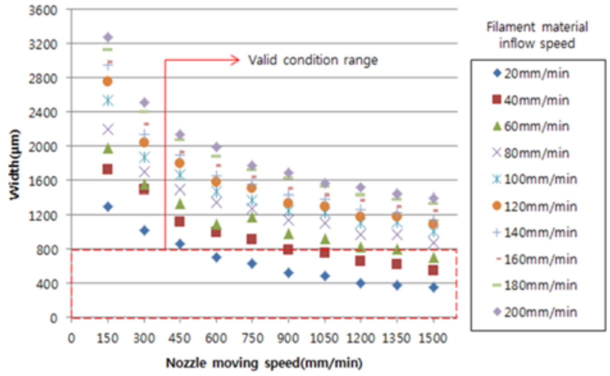

Fig. 6 Extruded-pressed line widths for various inflow speed and nozzle speed

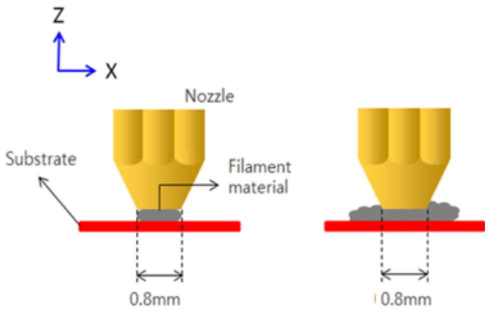

Fig. 7 Schematic drawing of extruded-and-compressed material between nozzle and substrate

The inner diameter and outer diameter of the nozzle were 0.4 mm and 0.8 mm, respectively. The thickness and width as well as cross-sectional shape were observed in x-z plane in Fig. 3 by changing the gap between the substrate and the nozzle as from 0.1~1.0 mm.

Fig. 4 is photographs of the cross-sectional image observed by optical microscope (OSM-U. Dong Won Co.) for various gaps between the substrate and nozzle (H). Maximum thickness and widths were measured using image processing software (IT PLUS-4.0, SomeTech Vision Inc.). As seen in Fig. 4, the width was decreased and the thickness was increased as the gap between nozzle and substrate increased. Moreover, when observing the cross-sectional shape, the thickness was even as the gap between nozzle and substrate was decreased. From these results, we can conclude that the thickness tends to even over the cross-section as the gap between nozzle and substrate is small. That is, a line with even thickness can help to fabricate a surface having good surface roughness. However, the width of the line is not uniform (458~558 μm) when the gap between nozzle and substrate is below 0.1 mm as shown in Fig. 5. It was because the material extruded improperly through the narrow gap between nozzle and substrate.

3.2 Width and thickness of the extruded polymer material

Further experiments were conducted to examine the thickness and width of the fabricated line according to the varying inflow speed (Q) and nozzle speed (V). Lines were fabricated changing the inflow speed and nozzle speed as 20~200 mm/min and 150~1500 mm/min, respectively. While the gap between nozzle and substrate was fixed as 0.1 mm. Fig. 6 is measured widths of fabricated lines for various inflow speeds and nozzle speeds. The extruded-and-pressed line widths decreased as the inflow speed decreased and nozzle speed increased. The minimum line width of 348 μm was observed at inflow speed and nozzle speed of 20 mm/min and 1500 mm/min, respectively. However, as seen in Fig. 7, it is possible that the extruded line thickness will be non-uniform if the width of extruded filament material is larger than the outer diameter of the nozzle. In this regard, we set a valid fabrication condition range as shown in Fig. 6 where the width is less than nozzle diameter of 0.8 mm.

Fig. 8 is line width and thickness for various nozzle moving speeds in valid condition ranges. The inflow speed was set as 20 mm/min, and the distance between nozzle and substrate was 0.1 mm. As seen in Fig. 8, the thickness was almost identical of 120 μm at any nozzle moving speed although the width changed according to the nozzle moving speed. However, the thickness was larger than the gap between nozzle and substrate of 100 μm. It is because the material suffered compress load between nozzle and substrate and the load was released when the nozzle passed by. This phenomenon is known as Swell.[18] In this regard, the layer thickness can be different from the gap between nozzle and substrate.

From these results, we can conclude that the line width could be changed during FDM process with identical hardware. That is, lines of wide and narrow width can be fabricated as needed in a process. Consequently, the fabrication speed, as well as the resolution, can be increased. In this regard, we generated a formula with fabrication conditions as well as line widths using Matlab R2011b. In Curve Fitting

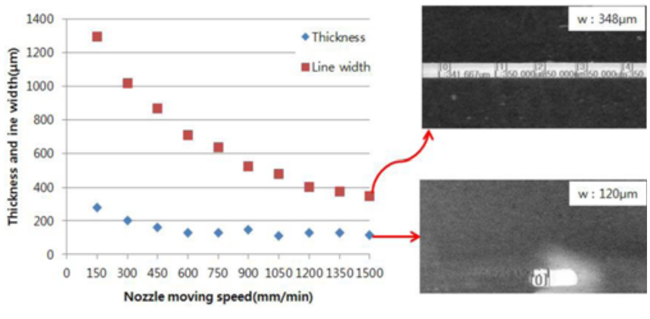

Fig. 8 Line width and thickness in valid condition range for nozzle moving speed

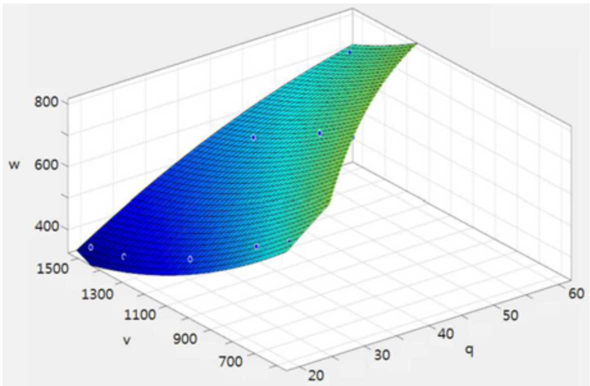

Fig. 9 3-dimensional graph of derived polynomial

Tool of Matlab, an n-th polynomial is expressed as Eq. (1).

$$y = \sum_{i=1}^{n+1} p_i x^{n-i-i} \tag{1}$$

Where, n is order of polynomial and p is coefficient. The polynomial of maximum R-square value can be induced Using Eq. (1). The nozzle moving speed (V) and inflow speed (Q) were used as input values (independent variables) while the gap between nozzle and substrate was fixed as 0.1 mm. The dependent variable was width of the extruded-pressed filament material. Eq. (2) is derived equations for the width of filament material ($f(Q, V)$) as function of inflow speed (Q) and nozzle speed (V). Therefore, we can change the fabricated line width in a process by changing the inflow speed and nozzle speed. Fig. 9 is a 3-dimensional graph of derived polynomial.

$$f(Q,V) = 774.8 + 22.94Q - 0.8841V - 0.09726Q^2 \\ - 0.004035QV + 0.0002639V^2 \tag{2}$$

4. Surface Fabrication and Application

Lines are fabricated side-by-side to form a surface in the FDM system. In this regard, as seen in Fig. 10, it is conjectured that the fabrication distance (δ) between lines is mainly influenced on the surface roughness. To examine the effect of fabrication distance on the surfaces roughness, flat surfaces were fabricated by changing fabrication distances from 0.3 to 0.35 mm. The inflow speed and nozzle speed were 20 mm/min and 1500 mm/min, respectively. The gap between nozzle and substrate was set as 0.1 mm. The line width was 348 μm by these fabrication conditions as represented in Fig. 8.

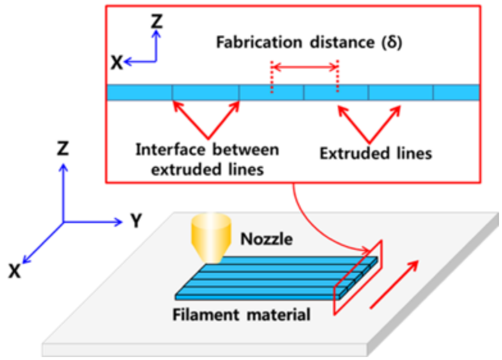

Fig. 10 Schematic drawing of the surface fabrication in the FDM system

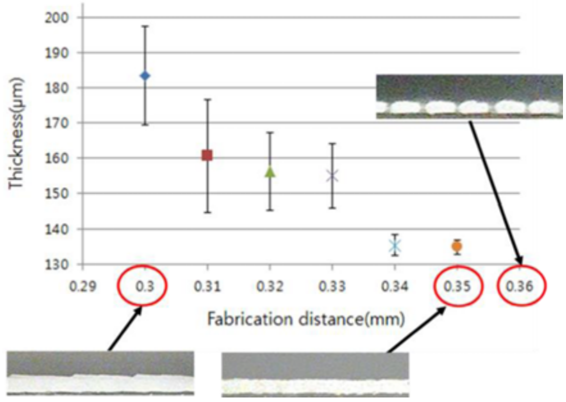

Fig. 11 Surface thickness for the fabrication distance change

Cross-sectional shape was investigated to determine the thickness variation using an optical microscope and image processing. Fig. 11 summarizes deviations of measured surface thicknesses for the fabrication distance change. As seen in Fig. 11, the deviations decreased as the fabrication distance increased. That is, as the fabrication distance increases, a better surface roughness can achieved. Furthermore, the best surface roughness (2 μm of deviation) was measured at fabrication distance of 0.35 mm. Moreover, as the fabrication distance is larger than line width, for example at 0.36 mm, the surface reveals discontinuity. In this regard, we can conclude that a surface of best roughness will be fabricated when the fabrication distance is same as the line width.

Fig. 12 is cross-sectional shape comparisons of commercialized 3D printers with our experiment result (δ = 0.35 mm). Dimension 1200es sst (Stratasys Inc.), FB-9600 (TPC Mechatronics) and 3DP-110F (HyVISION Systems) were used as commercialized 3D printers. All the fabrications, commercialized systems as well as experiments, were with same inner diameter of nozzle (0.4 mm) and filament diameter (1.75 mm). Thickness deviations of Dimension 1200es sst and 3DP-110F were 24 μm and 23 μm, respectively. Rapid peak and valleys were observed in both specimens. Moreover, for FB-9600, discontinuities were observed.

Fig. 13 shows the result of measuring the surface roughness using

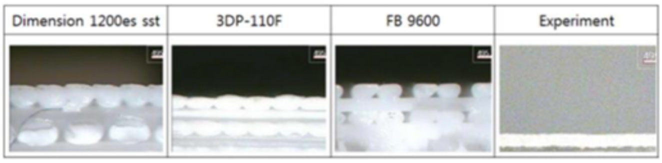

Fig. 12 Cross-sectional shape comparisons of commercialized 3D printers with experiment result

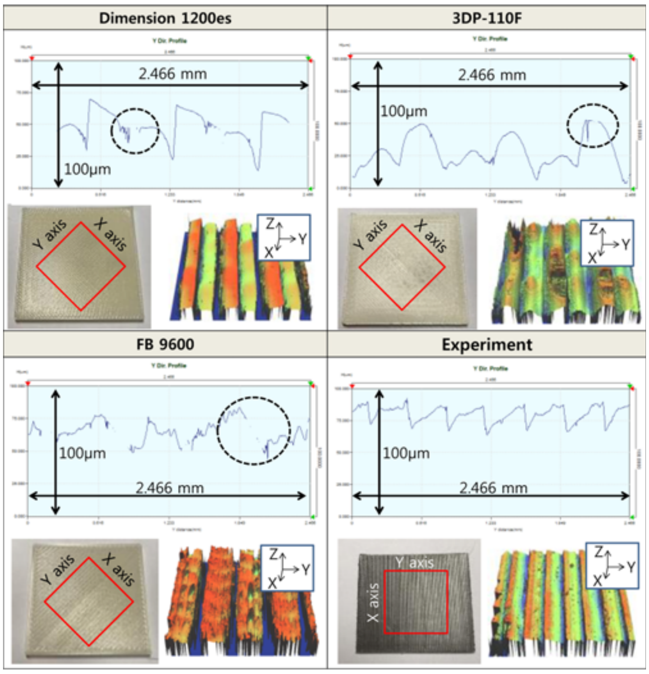

Fig. 13 Surface roughness measurement results

a laser surface measuring device (Nanoview, NanoSystem Co., Ltd.). As can be seen in Fig. 13, some part of the specimens made with commercially available 3D printers have surface features that are outside the measurement range of the measuring device (dotted circles). Therefore, the appropriate R_a value could not be obtained. However, the surface shape of the experimental result was within the measurement range of the device and the R_a value was 1.38 µm. From these results, it can be concluded that a better surface roughness can be achieved only adjusting fabrication parameters such as the gap between nozzle and substrate, inflow speed of filament and nozzle speed without changing hardware configurations.

A multi-material 3D printing technology is being focused as next-generation 3D printing technology. Especially, 3-dimensional circuit device fabrication (3DCD) technology based on 3D printing and liquid material dispensing is expected for manufacturing electronic devices without PCB.[5-8] In this regard, liquid conductive material, which takes the role of electric connection among electronic elements, was dispensed on improved surface. Moreover, for comparison, same conductive material was dispensed on a surface fabricated using a commercialized FDM system (Dimension 1200es), too.

The conductive materials were dispensed in two directions as seen in Fig. 14. The 0° direction means that conductive material dispensing and polymer material extrusion direction are the same. The 90° direction means dispensing and extrusion direction is rectangular. The fabrication conditions for FDM surface were the same as for those of Fig. 12. The conductive material (ELCOAT-P100, Cans Co.) dispensed at the speed of 10 mm/sec. As seen in Fig. 14, dispensed line widths on improved surface are almost identical in all directions. However, for Dimension 1200es sst, there is almost no deviation in width in 0° direction. But, in width in 90° direction, width was drastically changed. In this regard, an electrical circuit can be fabricated in any direction on improved surface.

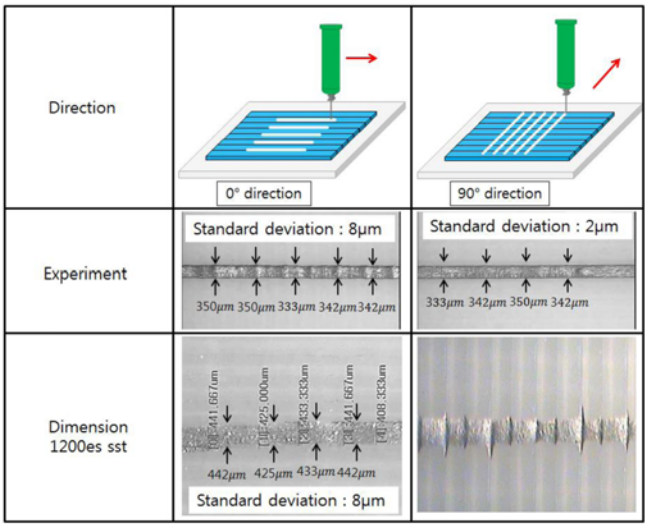

Fig. 14 Conductive materials dispensing on FDM surfaces

5. Conclusion

In this research, the FDM-based multi-material additive manufacturing (AM) system was developed. Line fabrication experiments were conducted using FDM head to examine whether the fabrication parameters has an effect on the surface roughness of the fabricated structure. From the experimental research, it was found that the thickness of the line tends to even over the cross-section as the gap between nozzle and substrate is small. The line widths decreased as the inflow speed and nozzle speed increased. Moreover, the line thickness will be non-uniform if the width of extruded line is larger than the outer diameter of the nozzle. The thickness of the line is larger than the gap between nozzle and substrate due to the residual stress in the extruded line. Based on these results, an empirical formula for the line fabrication was made. A surface of best roughness will be fabricated when the fabrication distance is same as the line width. As an application, an electrically conductive liquid material was uniformly dispensed on the improved surface, successfully.

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