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Fabrication of fine metal patterns using an additive material extrusion process with a molten metal

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A B S T R A C T

The objective of this work is to establish a volumetric metal 3-dimensional (3D) printing system based on material extrusion method and to fabricate metal patterns by investigating various process variables. Numerical heat transfer simulation was conducted to design the nozzle system with a minimized heat loss at the nozzle tip. Based on the simulation results, a metal 3D printing system with X, Y, and Z stages was constructed. The effects of lead content in molten metals and printing conditions such as stage speed and flow rate were investigated. The line formation like bulged, uniform, and dashed lines was evaluated using an optical microscope, and the variation in line widths of uniform lines was investigated with the process variables. Various types of 2-dimensional (2D) patterns were fabricated with an optimized process variable. A simple 3D structure was obtained to demonstrate the feasibility of the proposed system and procedure.

1. Introduction

Three-dimensional (3D) printing technology, also called additive manufacturing, is a manufacturing technology that revolutionizes existing subtractive manufacturing for fabricating structures using 3D modeling files like stereolithography (STL) as an output source [1,2]. It is advantageous for the fabrication of prototypes and small quantity production of various kinds because users can easily change the shape of a printed product. This technology has recently become widely available for home use due to this distinct characteristic. In recent years, research has been conducted using metal materials instead of conventional plastic materials like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyethylene terephthalate (PET) or nylon in order to converge with the industrial field.

Among various printing methods that use metal materials, powder bed fusion (PBF), binder jetting (BJ), and direct energy deposition (DED) are mainly used in the metal 3D manufacturing process. Using the above methods, convergence and research with the medical and mechanical industries for products such as medical implants, rehabilitation tools, molds and mechanical products are common [3–8]. In addition, studies on the effects of printing process conditions, material properties, pre-processes, and post-processes have been conducted to improve the mechanical and electrical properties of printed objects [9–12]. However, the above methods require a heat source of high temperatures such as a laser for use with metal powder, which requires a large space and high cost. For these reasons, these methods are not suitable for fabrication of electronic devices.

For the fabrication of electronic devices, studies have mainly been conducted using the material extrusion (ME) method. The ME method consists of a simple mechanism for discharging the material through a nozzle from a reservoir. In addition, because the technology does not use metal powder, it is possible to manufacture an embedded structure and to reduce costs. Some researchers have studied the fabrication of capacitors, antennas, and batteries using the ME method [13–15]. However, these methods require a sintering process at temperatures of hundreds of °C due to use of nanoparticle materials containing binders.

We have developed a volumetric metal 3D printing system that can dissolve and eject molten materials which is binder-free in order to solve aforementioned drawbacks and investigated the feasibility of metal 3D printing. As can be seen in the Fig. 1, a dispenser with a shape capable of minimizing heat loss at the nozzle tip was constructed and evaluated through the heat transfer simulation. In order to optimize printing conditions for the first layer, which is the most important layer in 3D printing technology, we investigated the effects of stage speed, flow rate and lead content in the materials on line instability of the printed lines. Based on the above experimental results, a simple thin wall structure was fabricated.

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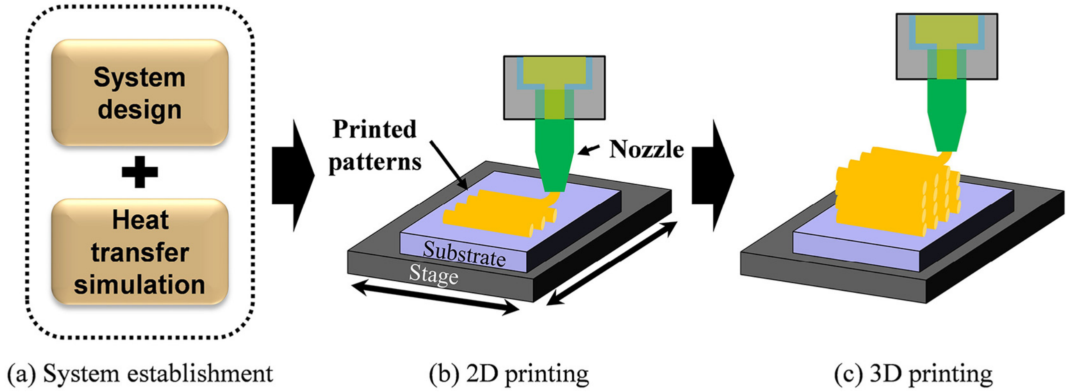

Fig. 1. A schematic of this work. (a) Establishment of the metal 3D printing system based on the design and heat transfer simulation; (b) characterization and evaluation of 2D printing; (c) fabrication of a 3D structure.

2. Experimental details

2.1. Heat transfer simulation

We designed all parts of the dispenser including the nozzle cap in order to minimize the heat loss at the nozzle tip using a CAD program (Fig. 2(a)). We then conducted a steady-state heat transfer simulation using ANSYS 16.0 to investigate if the conceptual design was valid. The barrel, the nozzle, the piston, and the heater were SUS304; the insulator was glass wool; the case was composed of polyether ether ketone (PEEK), and the heating block and the nozzle cap were made of aluminum. Thermal properties of each material are described in Table 1. Two O-rings which is made of perfluoroelastomer with the thermal conductivity of 0.17 W/m·K were inserted to seal the gap between the piston and the barrel. The location of thermocouple attached is marked with a red circle (Fig. 2(a)). The model for the analysis was produced with the same dimensions as the conceptual design (Fig. 2(b)), and the numbers of mesh and element were 51,674 and 16,770, respectively (Fig. 2(c)). All surfaces in contact with an ambient air were set to a constant temperature of 22 °C. The convectional heat transfer coefficient was assumed to 20 W/m^2·K. The temperature of the heater was set to 250 °C as an initial condition. From the simulation results, the temperature of the nozzle tip was estimated. Based on these results, we established a metal 3D printing system and evaluated heat flow from the nozzle tip. The system was heated to 250 °C for evaluation. After 10 min, the temperature at the nozzle tip was measured using a K-type thermocouple. The temperature of the case and the piston was also measured to assure safety during the experiment.

2.2. Establishment of a 3D printing system

We characterized the process conditions of 2D printing to obtain the stable first layer. The effects of stage speed and flow rate on line formation were investigated. The above experiment was conducted using

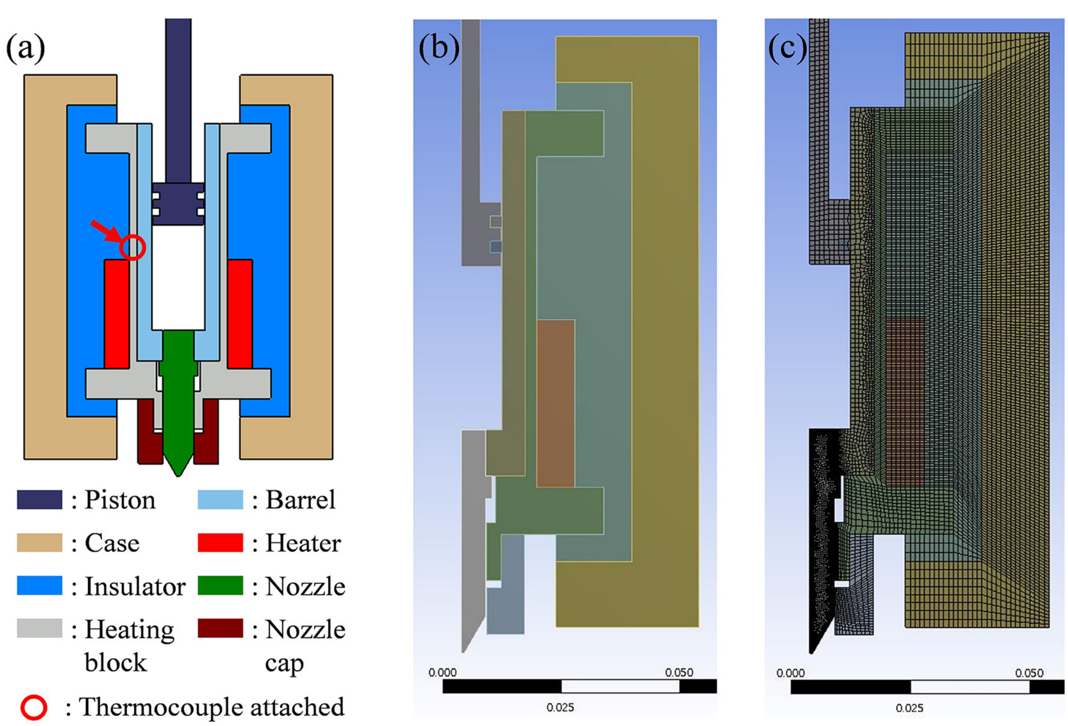

Fig. 2. (a) Concept design of the volumetric dispenser and (b) the model and (c) mesh of the heat transfer simulation. The unit of scale bars is a meter.