Sensors and Actuators A 268 (2017) 101–109

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Laboratory simulation of capacitance-based layer-by-layer monitoring of three-dimensional printing

D.D.L. Chung*,[1], Sanjaya Somaratna

*Composite Materials Research Laboratory, Department of Mechanical and Aerospace Engineering, University at Buffalo, The State University of New York, Buffalo, NY 14260-4400, USA*

ARTICLE INFO

*Article history:*
Received 19 August 2017
Received in revised form 16 October 2017
Accepted 26 October 2017
Available online 28 October 2017

*Keywords:*
3D printing
Polymer
Metal
Aluminum
Monitoring
Sensing

ABSTRACT

This paper provides a novel method of three-dimensional (3D) printing monitoring. The method is applicable to monitoring the printing of metals and polymers. The effectiveness of the method is shown by laboratory simulation. The method involves two coplanar electrodes that are electrically conductive and positioned on a substrate (build plate), which is substantially electrically non-conductive. The proximate edges of the electrodes are essentially parallel and are separate from one another. The area of the electrodes is substantially smaller than the area of the substrate. An AC current flows between the two electrodes, such that it partly flows in each of the layers in the build. In the monitoring, the capacitance between the two electrodes is measured using an LCR meter at 2.000 kHz. The AC voltage is 1.000 V. In case of metal printing, the demonstration involves aluminum layers (16 μm thick) on an alumina substrate and the two electrodes are preferably electrically connected. The layer-by-layer monitoring is effective for electrode spacing up to 76 mm. The electric field between the two electrodes spreads to the regions beyond the region between the two electrodes, thus enabling the monitoring of printed layers in the region between the electrodes as well as the regions in the vicinity of the electrodes. The technique is effective for following the progress of layer-by-layer printing and for detecting defects in a printed layer.


## 1. Introduction

The field of three-dimensional (3D) printing [1–7] is growing explosively, due to its importance for rapid prototyping, custom manufacturing and the manufacturing of complex shapes. This printing method involves layer-by-layer printing so that the totality of the layers corresponds to the 3D object. In spite of the growth and importance of 3D printing, the printed object is often not perfect, due to the inadequate control of the dimensions, the presence of pores, the variation of the composition, etc. This problem is more severe for metal printing than polymer printing, due to the high temperatures used in the former and the tendency for metals to be oxidized [8].

The assessment of the perfection of a 3D printed object (with the printing completed) can be performed by microscopy, x-radiography, ultrasonic inspection, and eddy current inspection (which applies to metal printing and does not apply to polymer printing). Although such assessment provides valuable information on the defects, it does not enable the removal of the defects in the object that has already been printed. On the other hand, if the assessment is conducted during the printing (rather than after the printing), the defects in a particular layer can be identified as the layer is printed. With this information, the printing process can be suitably adjusted so as to avoid the formation of such defect in the subsequent layers to be printed. This renders the printing smart, as in smart manufacturing. Furthermore, the layer-by-layer assessment during the printing provides a layer-by-layer record of the quality of the printed object. Therefore, the development of methods of 3D printing monitoring is much needed.

Previously reported methods of 3D printing monitoring mainly involve surface topographic imaging (for examining the dimensions and pores), interferometric measurement of the layer thickness, optical analysis of the degree of curing of the resin, and thermal infrared imaging (for observing the temperature distribution during the printing) [9–12]. These methods suffer from low spatial resolution and inadequate sensitivity to microscopic defects. In case of interferometric methods, an additional problem relates to the requirement that the material is transparent. Furthermore, the required placement of cameras or measurement components close to the local area of the object being printed complicates the implementation of these methods.

* Corresponding author.
*E-mail address:* ddlchung@buffalo.edu (D.D.L. Chung).
[1] http://alum mit edu/www/ddlchung.

https://doi.org/10.1016/j.sna.2017.10.061

The modification of the polymer for 3D printing by the incorporation of carbon fiber has been used to achieve conductivity, so that the electrical resistance of the resulting composite provides an indicator for the sensing of strain and damage after the printing [13]. However, this is not monitoring during printing.

The effects of printing conditions and stress on the out-of-plane capacitance and electric permittivity of a 3D-printed polymer have been reported by the authors [14,15]. The effect of the layer printing sequence on the molecular structure of 3D-printed polymer has been shown by the authors by in-plane capacitance measurement [16]. Due to the large difference in electrical conductivity between a polymer and a metal, the feasibility of capacitance measurement for a polymer does not imply the feasibility of the measurement for a metal. In fact, capacitance measurement is commonly assumed to be not feasible for an electrically conductive material such as a metal, and there is no prior report of such a measurement.

This paper provides a novel method of 3D printing monitoring that involves capacitance measurement. The installation of devices in the printer is not necessary. Only electrical contacts need to be placed on the build plate. This paper provides a laboratory simulation of the capacitance-based layer-by-layer monitoring for both polymer printing and metal printing. Relevant to the laboratory simulation are a wide variety of printing methods, which include Material Jetting, 3D Inkjet Printing (3DP), Polyjet Printing (MJP), Material Extrusion, Directed Energy Deposition (DED), Laser Metal Deposition (LMD), metal-wire-based Electron Beam Melting (EBM), and Fused Deposition Modelling (FDM).

The objectives of this work are (i) to demonstrate the feasibility of capacitance-based monitoring of 3D polymer and metal printing through laboratory simulation, (ii) to develop the methodology for this monitoring technique, (iii) to assess the efficacy and limitation of this technique, (iv) to apply this technique to the sensing of the progress of the layer-by-layer printing by monitoring the number of layers (or fractions of a layer) printed, and (v) to apply this technique to the sensing of defects in a printed layer. This paper is more focused on the layer-by-layer monitoring than the defect detection. The simulation performed in this work is real (not virtual) and pertains to ex-situ monitoring, i.e., capacitance measurement after various extents of 3D printing. The material studied is not 3D printed, but the material configuration resembles that of a 3D-printed material. This paper is directed at laying the initial groundwork that can lead to in-situ monitoring during printing.

## 2. Experimental methods

The laboratory simulation involves layer-by-layer stacking of a material in the form of a thin sheet, with the stack being built on top of a substrate, and measuring the in-plane capacitance of the stack using coplanar electrodes that are on the substrate away from the stack.

Four configurations are used. Configuration I (Fig. 1) involves an unmodified paper (commercial writing paper with conventional cellulosic fibers) substrate, whereas configuration II (Fig. 2) involves a modified paper substrate. The substrate modification in configuration II involves the presence of 15 slots that are equally spaced at a distance of 2.0 mm and are all perpendicular to the surface of the substrate and are parallel to the proximate edges of the electrodes. The slots are made using an office paper cutter and serve to decrease the contribution of the substrate to the measured capacitance of the system consisting of the substrate and the stack. By decreasing the substrate contribution to the measured capacitance, the sensitivity of the monitoring of the stack built on the substrate is enhanced, as shown in this work.

The stack consists of 1–20 layers. In case of a single layer, various fractions of a layer are used, such that each fractional layer is

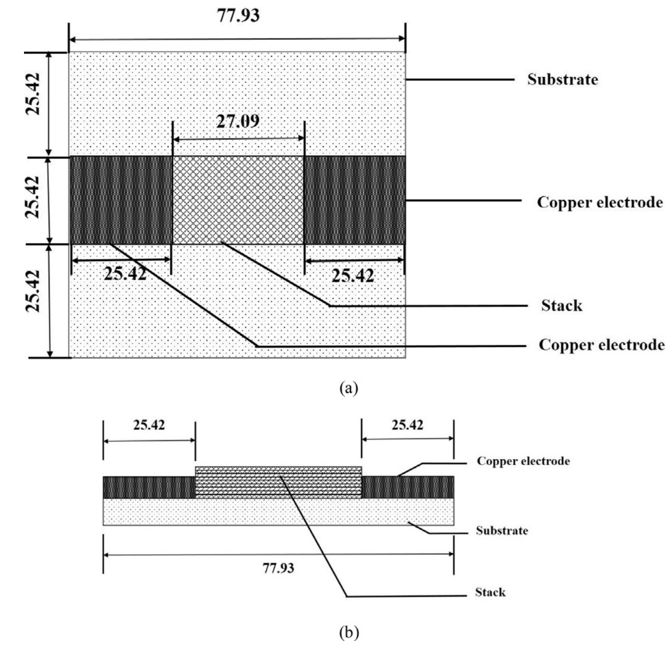


**Fig. 1.** Testing configuration I involving paper on an unmodified paper substrate (without slots). The stack is positioned in the region between the two electrodes. The two co-planar copper electrodes are positioned on the two sides of the printing region and are on top of the substrate. The insulating film is present between the electrode and substrate for metal printing monitoring, but not for polymer printing monitoring. All dimensions are in mm. The vertical dimensions are not to scale. (a) Top view. (b) Side view.

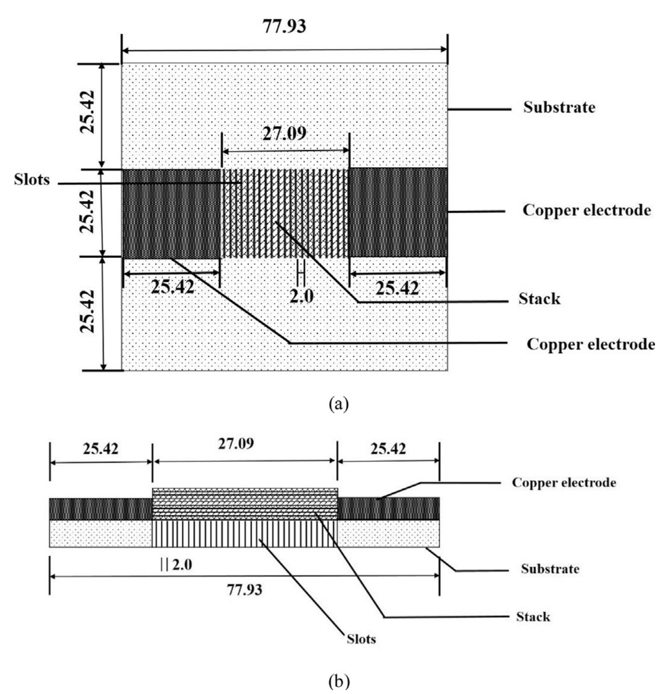


**Fig. 2.** Testing configuration II involving paper on a modified paper substrate (with slots). The stack is positioned in the region between the two electrodes. The two co-planar copper electrodes are positioned on the two sides of the printing region and are on top of the substrate. The insulating film is present between the electrode and substrate for metal printing monitoring, but not for polymer printing monitoring. All dimensions are in mm. The vertical dimensions are not to scale. (a) Top view. (b) Side view.