Research
3D Printing—Review

Engineering 2015, 1(1): 113–123
DOI 10.15302/J-ENG-2015014

Additive Manufacture of Ceramics Components by Inkjet Printing

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ABSTRACT In order to build a ceramic component by inkjet printing, the object must be fabricated through the interaction and solidification of drops, typically in the range of 10–100 pL. In order to achieve this goal, stable ceramic inks must be developed. These inks should satisfy specific rheological conditions that can be illustrated within a parameter space defined by the Reynolds and Weber numbers. Printed drops initially deform on impact with a surface by dynamic dissipative processes, but then spread to an equilibrium shape defined by capillarity. We can identify the processes by which these drops interact to form linear features during printing, but there is a poorer level of understanding as to how 2D and 3D structures form. The stability of 2D sheets of ink appears to be possible over a more limited range of process conditions that is seen with the formation of lines. In most cases, the ink solidifies through evaporation and there is a need to control the drying process to eliminate the "coffee ring" defect. Despite these uncertainties, there have been a large number of reports on the successful use of inkjet printing for the manufacture of small ceramic components from a number of different ceramics. This technique offers good prospects as a future manufacturing technique. This review identifies potential areas for future research to improve our understanding of this manufacturing method.

KEYWORDS additive manufacture, 3D printing, inkjet printing, ceramic components

1 Introduction

Inkjet printing was one of the first technologies to be developed for additive manufacture. In 1992, Sachs et al. at MIT described a method for manufacturing ceramic casting cores and shells by inkjet printing a binder phase onto a ceramic powder bed [1]. The binder phase acts as an adhesive, collectively binding the ceramic powder where it is printed, and leaving loose unconsolidated powder elsewhere. Once a layer has been printed, the powder bed is lowered and new powder is applied. This new layer has a second binder pattern printed onto it. An object is printed by repeating this process of lowering, adding fresh powder, and binder printing. The final printed object can be removed from the unconsolidated powder prior to final sintering, if required. This methodology has proved to be very versatile, and has been developed with new materials beyond those in its initial application concept. Today, additive manufacture by inkjet printing has applications in biomaterials, functional ceramics, and other areas. It has led to a low-cost method for the rapid fabrication of models, as well as highly successful commercialization.

A few years later, Xiang et al. at Brunel University, UK, developed another inkjet printing method—direct inkjet printing—in which a ceramic object is printed by the ejection of drops of ceramic powder suspended in a liquid slurry [2]. These drops dry to form a ceramic green body. Thus, by means of appropriate overprinting, a 3D object is constructed layer by layer in a conventional additive manufacture process. Figure 1 shows an example of a small inkjet-printed and sintered ceramic object from Ainsley et al. [3]. Direct inkjet printing is a more versatile printing method than powder-bed printing, because it allows the deposition of a large number of materials in parallel, solely limited by the complexity of the printing platform. Note that printing four materials

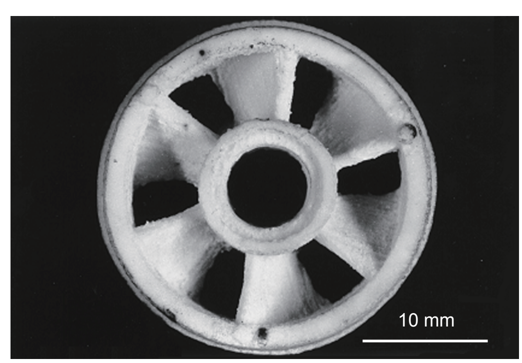

Figure 1. Example of a small ceramic object fabricated by an inkjet printing additive manufacture process. (Reproduced from Ref. [3] with permission from Springer Science+Business Media)

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Received 2 March 2015; received in revised form 25 March 2015; accepted 27 March 2015

in parallel is already a standard requirement for full color graphics (red, yellow, blue, and black); hence, the development of multiple-material printing platforms is not a serious technical challenge. Once it is possible to deposit different materials, inkjet printing can be used to manufacture heterogeneous ceramic bodies and structures with graded composition [4].

The versatility of additive manufacture with direct inkjet printing lies in the nature of the ink. Inks can be made that are precursors to many engineering materials, either in the form of particulate suspensions or as solutions. Of course, there are limitations to ink design. The first of these limitations is that the ink must undergo a transition to a solid after printing, and the printed solid may require further treatment to achieve the desired material composition and microstructure. The second limitation is that the ink must be printable; that is, it must satisfy a range of physical constraints to allow reliable and repeatable drop formation at the printing orifice of an inkjet printer.

This article will limit its scope to direct inkjet printing as a method for fabricating ceramic parts by additive manufacture; this distinguishes it from earlier reviews of inkjet printing for manufacture and ceramic fabrication [5–8]. It considers the drop-generation mechanism and the constraints this mechanism imposes on ink properties. In addition, this article discusses interactions between printed drops and the formation of 3D objects. An important consideration is the mechanisms that lead to defect formation during these processes, and whether inks can be designed to reduce their incidence.

2 Inkjet printing

The 19th century physicist Lord Kelvin (William Thomson) was the first to consider the possibilities inherent in the controlled direction of liquid through electrostatic forces, and even had a patent granted on this concept [9]. However, it is not clear from Kelvin's patent whether his device would have created discrete drops or a stream of liquid. In any case, this was an idea before its time, because there was no way to provide detailed instructions to steer the droplets, and thus the device was incapable of drawing patterns except on a single line, limiting its patterning to the simple dots and dashes of Morse code. It was almost 100 years before the next development in this field occurred in the 1950s, when Siemens used this technique to replace galvanometric chart recorders [10]. Major advances in both drop-generation and drop-placement technology then occurred, developing inkjet printing further and making it practical for computer graphics output. Advances in manufacturing technology reduced both the cost and size of these printers, so that today, inkjet printers are seen as a relatively cheap personal or desktop printing solution.

The main commercial applications for inkjet printing remain in graphics, product marking, coding, and dating, among other conventional printing operations. However, in recent years there has been considerable interest in, and use of, inkjet printing as a fabrication tool in a number of technological areas. These areas include displays [11], plastic electronics [12], ceramic component manufacture [13], and tissue engineering [14]. It is now clear that inkjet printing is on the verge of becoming a ubiquitous manufacturing tool.

2.1 Methods of drop generation

There are currently three mechanisms that are used in the commercial droplet generators required for inkjet printing. These mechanisms can be conveniently classified as continuous inkjet printing (CIJ), drop-on-demand inkjet printing (DOD), and electrostatic inkjet printing (EIJ). Each of these methods has its own particular requirements for the physical properties of the ink and a characteristic drop size range. Of these methods, both CIJ and DOD have a background in text printing and marking applications, and have been in commercial use for over 40 years.

CIJ generates a stream of drops through the Rayleigh instability of a liquid column ejected through a small nozzle. The nozzle is held at a potential relative to ground that transfers a small charge onto each drop. Individual drops are steered by applying another potential to deflector plates (Figure 2). Drop diameters are normally > 50 μm and are slightly larger than the diameter of the nozzle. CIJ printers produce a continuous stream of drops; unwanted drops (when no printing occurs) are deflected into a gutter, and are normally recycled in many graphics applications to prevent waste. Drop generation rate can be > 50 kHz and drops are ejected at velocities > 10 $m \cdot s^{-1}$. Although CIJ produces the greatest volume of ink per minute, it is limited in terms of placement accuracy. Its main application is in product marking and coding. However, there have been examples of using this method for the 3D printing of ceramics [15]. The main concern with this method is that the continuous fluid jetting leads to significant ink wastage and, if recirculation is used, the potential for ink contamination.

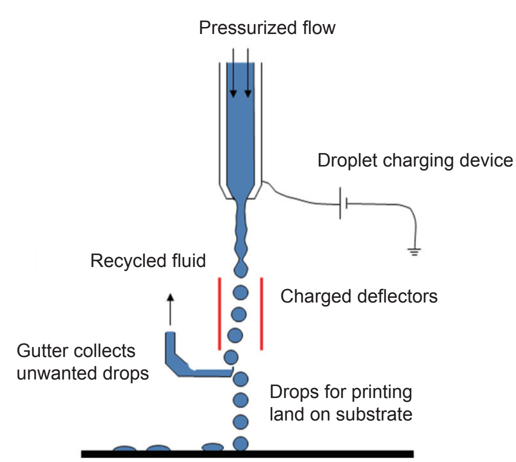

Figure 2. Schematic illustration of the operating principles of a continuous inkjet printer (CIJ). (Reproduced with permission from Ref. [7])

DOD printers generate individual drops when required, and do not steer a drop in flight. Drop placement occurs by mechanical positioning of the drop generator or substrate. Drops form through the propagation of a pressure pulse in a reservoir behind the nozzle. This pressure pulse must overcome the surface tension forces that hold the liquid drops in place; the resulting ejected column of liquid is pinched off to form a drop by a combination of surface tension forces and