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In-situ Droplet Inspection and Control System for Liquid Metal Jet 3D Printing Process

Tianjiao Wang[a], Tsz-Ho Kwok[b]* , Chi Zhou[a]

[a]*Department of Industrial and Systems Engineering, University at Buffalo, the State University of New York, Buffalo, NY 14260, U.S.A*

[b]*Department of Mechanical and Industrial Engineering, Concordia University, Montreal, QC H3G 1M8, Canada*

Abstract

Liquid Metal Jet Printing (LMJP) is a revolutionary 3D printing technique in fast but low-cost additive manufacturing. The driving force is produced by magneto-hydrodynamic property of liquid metal in an alternating magnetic field. Due to its integrated melting and inkjeting process, it can achieve 10x faster at 1/10th of the cost as compared to current metal 3D printing techniques. However, the jetting process may be influenced by many uncertain factors, which imposes a significant challenge to its process stability and product quality. To address this challenge, we present a closed-loop control mechanism using vision technique to inspect droplet behaviours. This system automatically tunes the drive voltage applied to compensate the uncertain influence based on vision inspection result. To realize this, we first extract multiple features and properties from both frozen and dynamic images to capture the droplet behaviour. Second, we use a voting-based decision making technique to determine how the drive voltage should be adjusted. We test this system on a piezoelectric-based inkjeting emulator, which has very similar jetting mechanism to the LMJP. Results show that significantly more stable jetting behaviour can be obtained in real-time. This system can also be applied to other droplet related applications due to its universally applicable characteristics.

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Keywords: Additive manufacturing; metal jetting; process inspection; close-loop control; vision

* Corresponding author. Tel.: +1 (514) 848-2424 #3807; fax: +1 (514) 848-2424 #3175.
E-mail address: tszho.kwok@concordia.ca

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1. Introduction

Additive manufacturing (AM) or 3D printing has been hailed as the third industrial revolution in the unique way that products are designed and manufactured [1]. Due to the elegant concept of layer by layer fabrication, AM can build complex objects with a wide variety of materials and functions. This opens up tremendous opportunities for a wide range of applications including aerospace, automotive, defences, and biomedical industries [2]. With the advancement of material, machine, and process, metal 3D printing is now the fastest growing segment among 3D printing technologies [3]. However, most of the current metal 3D printing applications involve high cost and low-speed metal powder sintering or melting [4-7]. Recently, a revolutionary liquid metal jet printing (LMJP) alternative [8, 9] has been explored and recognized as a promising emerging process that can drastically lower manufacturing part costs while doubling existing printing speed. This game-changing technology is opening up unprecedented opportunities in advanced manufacturing.

Vader Systems, a startup company in Buffalo, NY, is developing and commercializing the world's first molten metal 3D printer using proprietary LMJP technology based on magneto-hydrodynamic inkjet printing process [8]. The LMJP technology patterns magneto-hydrodynamic liquid metal into complex 3D parts **10x faster at 1/10th of the part cost as compared to current methods** [8]. This includes the earth's most abundant metal – Aluminum, which has been widely used in mission-critical heavy industries, yet extremely challenging to handle by other metal printing technologies. The molten solid metal in LMJP rather than sintered powder leads to dense metal parts with much finer micro-structure that have 30% or greater increase in ultimate tensile strength [10]. The main structure of this system is shown in Figure 1.

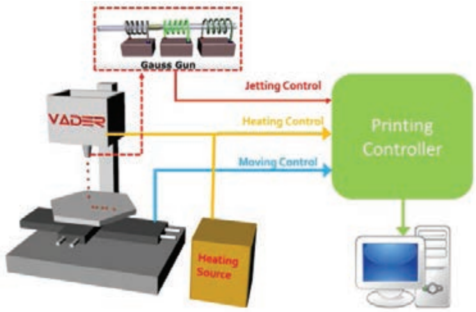

Figure 1: Liquid metal jet printing system

Though tremendous efforts and progress have been made in the LMJP process during the past few years, as a brand new technology, there are still multiple challenges such as the limited choice of material, e.g., has to be conductive or pre-charged, low melting point (660℃), and the difficulty in controlling the wetting property and coalescence behavior of the jetted metal droplet, which handicap its large-scale commercialization in practice. One of the major challenges is that LMJP process suffers from low process reliability and product quality issues. Physics-based modelling approach have been proposed to predict the process drift and suggest corrective actions. However, the complex printing process (energy-mater interaction, phase changing, thermal-mechanical interaction) and the limitation of current computational tools hinders its practical applications in 3D printing processes [11, 12]. This gap has been reported in recent additive manufacturing roadmap reports by both the government agencies and industrial stockholders [13-17]. Given the layer-by-layer nature of 3D printing, if the process drifts are not corrected in a timely manner, defects will propagate into subsequent layers, and thus deleteriously affecting the function integrity (fatigue, strength, geometric integrity) of the part. Currently, the metal 3D printing systems are in an open-loop configuration, and the measurement of part quality is done offline, leading to material and energy waste and even devastatingly affect the structural health conditions and infrastructural integrity of many important engineering systems, especially for mission critical applications such as aerospace, defence, and automobile areas. *In-situ* process monitoring and process control is promising to address this challenge. In order to fill in this research gap and advance the technology development, we develop and validate a novel closed-loop control system which has a vision-based droplet inspection and a decision making using voting technology. Specifically, droplet formation is one of the most important factors associated with the printing quality and reliability in inkjet metal 3D printing process. It is vital to *on-line* monitor and *real-time* control the jetting behavior including the droplet volume, speed, and location in jetting history, which would affect the geometrical and functional integrity of the printed part. The aim of this paper is to design and verify a sensing and detection module that can capture high-fidelity data of the droplet and extract critical information for the downstream decision making for *in-situ* correction, and ultimately improve the process reliability, reproducibility, and printing quality of LMJP process. The result from this paper will be a feedback control system that continuously monitors the pattern of the droplets in the LMJP process using the