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Review Article

3D metal droplet printing development and advanced materials additive manufacturing

Lawrence E. Murr[a,b,c,*], *Wayne L. Johnson*[c]

[a] *Department of Metallurgical, Materials and Biomedical Engineering, The University of Texas at El Paso, El Paso, TX 79968, USA*
[b] *W.M. Keck Center for 3D Innovation, The University of Texas at El Paso, El Paso, TX 79968, USA*
[c] *Arizona Technology Innovation Group, Phoenix, AZ 85044, USA*

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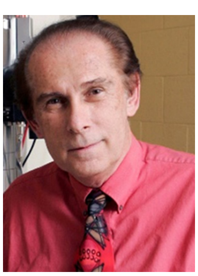
ABSTRACT

While commercial additive manufacturing processes involving direct metal wire or powder deposition along with powder bed fusion technologies using laser and electron beam melting have proliferated over the past decade, inkjet printing using molten metal droplets for direct, 3D printing has been elusive. In this paper we review the more than three decades of development of metal droplet generation for precision additive manufacturing applications utilizing advanced, high-temperature metals and alloys. Issues concerning process optimization, including product structure and properties affected by oxidation are discussed and some comparisons of related additive manufactured microstructures are presented.



Lawrence E. Murr has been in metallurgical and materials engineering education, research, teaching, and academic administration for more than 50 years at Penn State University, University of Southern California, New Mexico Tech, Oregon Graduate Center, and The University of Texas at El Paso, where he currently is Emeritus Professor. He has also been a member of the ATIG-Phoenix technical staff since 2014. The recipient of numerous distinguished research and teaching awards including The TMS 2007 Educator Award, The 2007 John S. Rinehart Award for global leadership in shock and high-strain-rate phenomena, the 2008 Henry Clifton Sorby Award for lifetime achievement in metallography, the 2009 Albert Easton White Distinguished Teaching Award of ASM International, the 2010 Piper Professor Award, the 2014 Alpha Sigma Mu Materials Science Distinguished Life Member Award, and Lee Hsun Distinguished Lecture Awards of the Shenyang National Laboratory for Materials Science, Institute of Metal Research, Shenyang, China (2010 and 2016). Dr. Murr has also published over 800 technical papers and 21 books, the latest being "Handbook of Materials Structures, Properties, Processing and Performance" published by Springer in 2 volumes in 2015. The holder of 5 patents, Dr. Murr also holds BS degrees from Albright College, and Penn State University as well as MS and Ph.D. degrees from Penn State. He is a Fellow of ASM International and a Registered Professional Engineer (Texas).

Abbreviations: AM, additive manufacturing; CAD, computer-aided design; DED, direct energy deposition; DMD, direct metal deposition; DMLS, direct metal laser sintering; EBF3, electron-beam free-form-fabrication; EBM, electron beam melting; LENS, laser engineered net shaping; HIP, hot isostatic pressing/processing; RP, rapid prototyping; SL, stereolithography; SLM, selective laser melting.

* *Corresponding author.*
E-mail: lemurr@utep.edu (L.E. Murr).

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Wayne L. Johnson has been CEO and managing partner of the Arizona Technology Innovation Group, LLC (ATIG-Phoenix) since 2008. ATIG is a group of experienced technical leaders that initiate technical projects with significant impact potential on manufacturing systems. Prior to consulting, he was COO of Tokyo Electron Phoenix, President and owner of Prototech Research Inc., Technical Manager of Epsilon Technology, and Technical Director of (ACS) Advanced Crystal Sciences, Inc. Before ACS, he was Group leader in Target Fabrication at Lawrence Livermore National Labs fabricating microfusion devices for the laser fusion program. Dr. Johnson holds a Bachelor in Physics, and Masters and PhD degrees in Electrical Engineering from the U. of Illinois with thesis work in plasma discharge physics and ion bunching. He has authored 65 patents, several papers and a book chapter.

1. Introduction

Discussions of new manufacturing paradigms usually invoke comparisons between more traditional subtractive manufacturing and additive manufacturing (AM), having historical roots which can go back nearly 150 years in the context of photo-sculpture, topography, and lithography in various forms [1]. Photolithography and stereolithography (SL) evolved as AM technologies using laser beams to cure (or solidify) photosensitive polymers leading to photolithography central to integrated circuit and multi-layer device fabrication which continues to evolve today. Simultaneously, powder spray and weld-metal overlay technologies evolved as a means to repair worn surfaces and associated surface degradation as well as surface (layer) modification or hardening using electron or laser beam melting of injected metal alloy or hard compound particles or powders [2–5]. A. Ciraud [6] in a 1972 patent, introduced the concept of metal layer fabrication by selectively melting powders using electron, laser or plasma beams. A decade later, Hikodama [7] described the first rapid prototyping (RP) system, while Herbert [8] almost simultaneously described the earliest 3D CAD-driven laser stereolithography system. This was followed by the founding of one of the first commercial AM companies by Charles Hull (ca. 1986) utilizing CAD-driven SL to build layer-by-layer solid structures. Other RP involving solid freeform fabrication (SSF) began to evolve in the late 1980 and early 1990 period, which utilized metal wire feedstock melted by laser or electron beams or similar schemes using powder feed delivery nozzles forming layer-by-layer solid objects as illustrated schematically in Fig. 1(a) and (b) [9,10]. Laser wire feedstock melting evolved as laser cladding-based technologies similar to weld surface cladding or direct metal deposition (DMD), a process referred to as laser engineered net shaping (LENS) of AM metal objects [11,12]. A similar process using electron beam melting of a feed wire in vacuum was also developed as electron beam free-form fabrication (EBF3) [13]. Laser sintering of powder as shown in Fig. 1(b) evolved as direct metal laser sintering (DMLS) or selective laser sintering (SLS), and both wire and powder feed processes have been referred to as direct energy deposition (DED) processes.

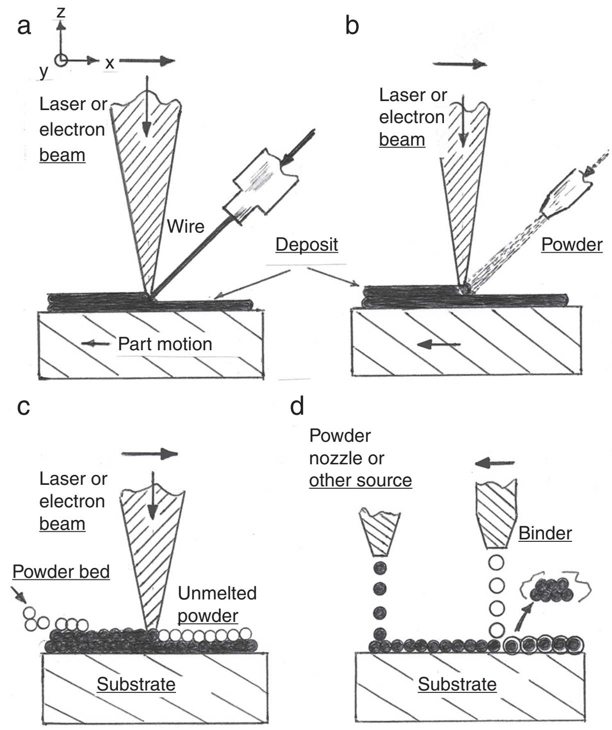

Fig. 1 – Schematic comparisons of metal AM processes and systems. (a) Laser or electron beam cladding using wire feed process. (b) Laser or electron beam sintering based systems. System can incorporate multiple powder feeders. (c) Powder bed fusion processes using electron or laser beam selective melting. Powder is rolled or raked from supply container or cassettes. (d) Binder jet powder process which requires post sintering to permanently bind metal powder and expel binder. Unbound powder is recovered.

Powder-bed fusion technologies also evolved in the 1990s in part as an extension of SLS. Two popular methodologies became commercialized as shown schematically in Fig. 1(c) [14]. In Fig. 1(c), powder from a reservoir is rolled into a layer which is selectively melted using a CAD-driven laser beam, while alternatively in Fig. 1(c), powder is gravity fed from cassettes which is racked into a layer and selectively melted by a CAD-driven electron beam. Fig. 1(c) uses an inert gas (Ar or N) environment for laser melting while electron beam melting is in vacuum. The laser melting process is referred to as selective laser melting (SLM), while the corresponding electron beam melting process is referred to as electron beam melting (EBM). A process devoid of laser or electron beam sintering or melting uses a powder bed, which is selectively spread in a layer from a movable powder nozzle. This is followed by selective dropping of a suitable binder from an ink-jet printer head directed by a CAD program to create a metal/binder product which is sintered at high temperature to remove the binder and sinter (solidify) the metal powder. This process, shown schematically in Fig. 1(d) is variously referred to as binder jetting [15], powder bed/inkjet printing, drop-on-powder printing, etc. The binder/powder product is extracted from the building process, and after removal of excess or unbound powder, is sintered at high temperature as the binder is vaporized. A variance of this