Precision Engineering 68 (2021) 197–205

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: http://www.elsevier.com/locate/precision

Current challenges and potential directions towards precision microscale additive manufacturing – Part IV: Future perspectives

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ABSTRACT

Microscale additive manufacturing is one of the fastest growing areas of research within the additive manufacturing community. However, there are still significant challenges that exist in terms of available materials, resolution, throughput, and ability to fabricate true three-dimensional geometries. These challenges render commercialization of currently available microscale additive manufacturing processes difficult. This paper is the last one in a four-part series of articles which review the current state-of-the-art of microscale additive manufacturing technologies and investigate the factors that currently limit each microscale additive manufacturing technology in terms of materials, resolution, throughput, and ability to fabricate complex geometries. Parts I, II and III offer prognoses about the future viability and applications of each technology along with suggested future research directions that could be used to bring each process technology in line with its fundamental, physics-based limitations. This paper brings together the general design guidelines that must be followed while designing scalable microscale AM processes. Finally, the paper concludes with an analysis of the role of precision engineering in the future advancement of microscale additive manufacturing technologies. This series of publications is a joint effort by the members and affiliates of the Micro-Nano Technical Leadership Committee of the American Society for Precision Engineering (ASPE).

1. Introduction

1.1. Introduction to additive manufacturing (AM)

Additive manufacturing (AM) technologies, colloquially known as ‘3D printing’, have been researched and implemented in low-volume production environments for more than two decades. Although, initially publicized as ‘rapid prototyping’, improvements in additive manufacturing technologies have predominantly led to the fabrication of near-net shaped final products which need minimal post-process machining. The first formalized terminology of AM was adopted by the ASTM Committee F42 in 2009, which defined it as the ‘process of joining materials to make objects from three-dimensional (3D) model data, as opposed to subtractive manufacturing methodologies.’ [1] Most AM processes are layer-by-layer (LbL) in nature, where each lamina/layer is deposited and consolidated sequentially. However, there are volumetric AM techniques which do not use an LbL approach. AM processes are mainly classified on the basis on starting material state (liquid, filament, paste, powder, and sheet), layering technique, and bed consolidation technique facilitated by energy mode and phase change

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Abbreviations: F-DIW, Flow-based Direct Ink Write; EHD Printing, Electrohydrodynamic Jet Printing; AJP, Aerosol Jet Printing; μ-SLA, Microstereolithography; TPL, Two Photon Photopolymerization/Lithography; LIFT, Laser Induced Forward Transfer; μ-SLS, Microscale Selective Laser Sintering; FIBID, Focused Ion Beam Induced Deposition; LCVD, Laser Chemical Vapor Deposition; MCED, Meniscus-confined Electrodeposition; LECP, Laser-Enabled Electrochemical Printing.

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https://doi.org/10.1016/j.precisioneng.2020.12.014
Received 21 April 2020; Received in revised form 13 December 2020; Accepted 14 December 2020

physics [2–4]. The primary advantages of AM over conventional and subtractive manufacturing techniques are design independence, multi-material fabrication capabilities, lower cycle times, reduced tooling costs, and higher degree of automation [2]. AM processes have received unprecedented attention over the last few decades with widespread applications in the automotive, aerospace and biomedical industries. A rather nascent sub-category of AM research is the development of microscale AM processes and tools for primary applications in the semiconductor, MEMS/MOEMS, and medical devices industries [5]. It is driven by an ever-increasing demand for miniaturization of products, and the scalability issues associated with existing micromanufacturing techniques.

From a strategic perspective, the projected socioeconomic impact of AM processes has mostly been hailed as a disruptive technology [6,7]. There have been visible improvements in supply chain efficiencies, time-to-market, and production customization of firms which have implemented AM techniques [8–11]. However, it is critical to understand the assumptions of these studies. Despite the perceived value proposition of AM, the degree of penetration of AM might vary from one industry to the other, which introduces several research opportunities to further define the scope of AM technologies. Although several exploratory studies exist in literature which have identified strong developmental frameworks for commercialization and adoption of AM techniques [12–14], their impact is not well characterized because of the range of the technical and economic challenges associated with these processes. For example, metal additive manufacturing can theoretically produce complex functional parts with lower weights, as compared to casting, forming and machining. However, the uniformity in microstructure growth and its effect on failure modes is still an active area of research [15]. This limits the adoption of metal AM processes like Selective Laser Sintering/Melting (SLS/SLM) to production of non-critical and spare components. Furthermore, there are several issues associated with developing a robust supply chain network for AM technologies, which are effectively stunting the unabated growth of these processes [16,17]. However, these challenges do not greatly undermine the potential of AM to be a revolutionizing technology.

1.2. Challenges associated with conventional micro/nano-manufacturing processes

The underlying need in micro/nano-manufacturing systems development is Function and Length-Scale Integration (FLSI) where the products' applications and robustness must be improved without significantly increasing their dimensions and weight [18,19]. Most of the existing micro/nano-manufacturing systems are enabled by multidisciplinary research and innovations in nanotechnology, precision engineering, and materials engineering. The semiconductor and chip fabrication industries have been the primary movers of these technologies. However, the growing demands for microproducts in other industries has led to a paradigm shift in defining the capabilities of these processes. Dimov et al. [18] classified the functional-level opportunities for creating new microproducts into five categories – (1) Enhanced force micro-actuation, (2) High aspect ratio features, (3) Environment resistance, (4) High precision, and (5) Unification and standardization of product integration/packaging.

The development trends towards miniaturization have been mostly product-driven and are concentrated in industries where cost and FLSI criteria are relatively well-satisfied [18–20]. These approaches ensure that there is a comprehensive understanding of the physical phenomena exploited by micro/nano-manufacturing technologies. However, challenges arise when the complete spectrum of complementary technologies is not available (or well understood) for FLSI. For example, realization of 3D freeform microproducts is difficult without integration of several micro/nano-manufacturing technologies. The constraints posed by each individual technology further dominate the product-design process [18,21]. These manufacturing limitations mark a departure from traditional product design philosophy by shrinking the overall design space, limiting FLSI, and driving innovation in technologies which are highly-product specific. The primary challenges associated with existing micro/nano-manufacturing processes are as follows:

1. *Limited geometric freedom*: Mature subtractive micromanufacturing processes like surface micromachining restrict the design space to 2/2.5D structures which might be functionally limited as well. Achieving high-aspect ratio 'true-3D' structures with feature sizes below tens of micron range is difficult for most subtractive and hybrid micromanufacturing processes due to fundamental challenges in process physics, system engineering, materials, and throughput.
2. *Limited materials processing capabilities*: Several non-metallic materials (Si, polymers, copolymers, ceramics) have been researched for IC fabrication. Although a combination of lithographic and micromachining technologies has effectively widened the range of applications for these materials, there are challenges associated with crystallographic anisotropy, surface integrity, homogeneity and material defects at length scales which compromise the seamless integration of mechanical, thermal and other functional properties into these microscale products/devices.
3. *Limited feature-size resolution and throughput*: A key aspect of micro/nano-manufacturing technology development is the areal resolution at which the processes can fabricate products. While resolution is mostly driven by the process physics (for example diffraction limits in lithography), micromachining processes like micromilling, microforming, and micro-EDM etc. are also limited by the available tooling. A similar reasoning can be extended for process throughput as well; but there has been continuous improvement in the industry for increasing the throughput by modifying specific process parameters and product design. However, achieving FLSI involves multiple process steps which not only add to the overall throughput, but also introduce several sources of error, thereby increasing the overall cost of manufacturing. Therefore, understanding the limits to resolution and throughput of micro/nano-manufacturing processes remains an active area of research.

It must be understood that individually addressing these challenges is insufficient. The interdependence of these parameters and external factors (like supply chain robustness and environmental policies) have a significant impact on the growth of the micro/nano-manufacturing processes. Multiple-pronged approaches and manufacturing frameworks have been suggested by researchers which would be critical to the holistic development of the industry [18].

1.3. Advantages and current state-of-the-art for microscale AM

These challenges can be addressed with the development of novel additive manufacturing techniques which can potentially provide greater design independence, multimaterial processing capabilities, and high throughput for complementing existent manufacturing framework. Microscale AM processes can also reduce the number of processing steps required to reliably fabricate a complex functional microproduct. Most commercially AM processes are limited to a feature-size resolution of tens of microns, which is a limiting factor for fabricating microproducts [22]. Relatively scalable state-of-the-art AM processes like Stereolithography (SLA), Selective Laser Sintering (SLS) and Inkjet-based techniques are further limited by their process physics and engineering tools [5]. The scalability of these processes in terms of the range of materials, feature-size resolution, geometric capabilities, and volumetric throughput are difficult to quantify without considering the fundamental and engineering challenges in the processes. Microscale AM processes can produce 2.5D structures repeatably, and can be reliably adapted to true-3D structures, which is a significant advantage over conventional micromanufacturing techniques. Unlike conventional processes, the design independence offered by microscale AM can ensure that the product development cycle is not limited by the process. The processes that have been discussed in this paper range from a resolution of hundreds of nanometers to hundreds of microns. Following certain design rules and ideas presented in this series of articles [23–26] can potentially improve these process for fabricating microscale true-3D parts.

1.4. Objective of this paper

This paper is Part IV of a four-part series of articles which discussed about the fundamental challenges and opportunities in microscale AM processes. Part I of the series talks about direct ink write processes, part II presents laser-based processes and part III highlights the challenges associated with deposition-based and hybrid electrochemical processes. The general objective of this paper is to help develop a comprehensive understanding of the current capabilities and limitations of various microscale additive manufacturing processes. As discussed in the previous sections, the primary advantage of AM processes is the design independence which can be leveraged in developing microscale parts and functional devices with applications in several industries. Although various innovative microscale AM processes, driven by novel physical phenomena exist in the literature, most of them are fundamentally limited in their capabilities. The processes have been evaluated on the basis of the following criteria – processable materials, geometric independence (2D, 2.5D, true-3D fabrication capabilities), minimum demonstrable feature-size resolution, and volumetric throughput. The fundamental limitations to these capabilities are primarily driven by the physics of the processes. Parts I-III [23,24,27] discuss these limitations in detail and analyze potential solutions. Furthermore, these articles also highlight the potential approaches that have been implemented in the literature to address these challenges and explores several auxiliary and complementary ideas to overcome the process limitations and enhance precision manufacturing. Based on these ideas, general guidelines and design principles have been discussed in this article to drive the integration of microscale AM processes in high-throughput production environments. This series of publications is a joint effort by the members and affiliates of the Micro-Nano Technical Leadership Committee of the American Society for Precision Engineering (ASPE).

2. Discussions and insights on the future development of microscale AM processes

The previous parts discussed the various microscale additive manufacturing processes that exist in either academia or industry [23,24,27]. The general motivation behind developing these processes is to facilitate the evolution of microfabrication industry, with the added advantages of an AM-based approach. The processes discussed in these sections are governed by a wide range of physical, chemical and electromechanical mechanisms. A comprehensive overview of the current state-of-the-art of these processes with detailed analysis of the feature-size resolution, fabrication geometry, volumetric throughput, and range of available materials for each process will be presented in this section. Table 1 provides a comparative overview of the process capabilities of each of the processes reviewed in this paper. The fundamental challenges which researchers generally encounter with microscale AM processes are also outlined in this section along with potential approaches to overcome them. This section provides a critical analysis of the process limits based on the four major criteria – materials, resolution, manufacturing geometry, and volumetric throughput. This section also identifies the general engineering approaches required towards enhancing precision freeform fabrication capabilities. Table 1 quantifies the performance characteristics of the microscale AM processes which have been discussed in the paper. Fig. 1 represents the operational windows of the processes; the feature size resolution (x-axis) versus volumetric throughput (y-axis) data from published research have been plotted.

2.1. General strategies to enhance materials capabilities

2.1.1. Overview of material capabilities of microscale AM processes

The seamless integration of microscale AM processes for aiding production-scale microfabrication techniques requires processing of a wide variety of materials. The potential applications of these processes are largely driven by the material classes that can be processed. The elemental composition, microstructural properties, and physical properties like electrical resistivity, mechanical strength, and surface roughness of the AM parts are key to the design of the process. In addition to the materials being processed, the substrate plays an important role in determining part adhesion, energy requirements (for laser-based processes), process parameters, post-processing conditions, and material handling.

Table 1

Performance data microscale additive manufacturing processes consolidated from previous research studies.

Process	Materials	Fabrication Geometry	Minimum Reported Resolution	Highest Theoretical Throughput at minimum resolution	References
Direct Ink/Jetting Processes					
F-DIW	Metals, Ceramics, Polymers	2.5D, 3D	600 nm	0.0005 mm^3/h	[28]
EHD Printing	Metals, Ceramics, Conductive polymers, Molten metals, Biomaterials, Quantum Dots	2.5D	50 nm	0.00036 mm^3/h	[29]
Binder Jetting	Metals and Ceramic powders	2.5D, 3D	3E+4 nm	166E+3 mm^3/h	[30]
AJP	Metals, Conductive Polymers, SWCNTs, Insulators	2D, 2.5D	1E+4 nm	50 mm^3/h	[31]
Laser Trapping and Curing Processes					
μ-SLA	Acrylic polymers	2.5D, 3D	2E+3 nm	6000 mm^3/h	[32,33]
Optical Tweezing	Silica, Polystyrene, Polymethyl Acrylate (PMMA)	2D, 2.5D	5 nm	3.655 mm^3/h	[34]
TPL	Polymers, Polymers with doped metals and CNTs	2.5D, 3D	120 nm	0.02–70 mm^3/h	[35]
Laser Heating Processes					
LIFT	Metals, Semiconductors, Conductive Polymers, Biomaterials	2.5D, ~3D	4000 nm	0.01 mm^3/h	[36]
μ-SLS	Metallic Nanoparticles, Polymer inks	2.5D, 3D	1000 nm	63 mm^3/h	[22]
Energy-Induced Deposition Processes					
FIBID	Metals, Insulators	2.5D, 3D	10 nm	3.6E-7 mm^3/h	[37]
LCVD	Metals, Metal Oxides, Silica	2.5D, 3D	500 nm	0.013 mm^3/h	[38]
Electrochemical Processes					
MCED	Metals, Conducting Polymers	2.5D, ~3D	50–100 nm	2.5E-7 mm^3/h	[39,40]
LECP	Metals, Semiconductors	2.5D, 3D	100 nm	28 mm^3/h	[41,42]

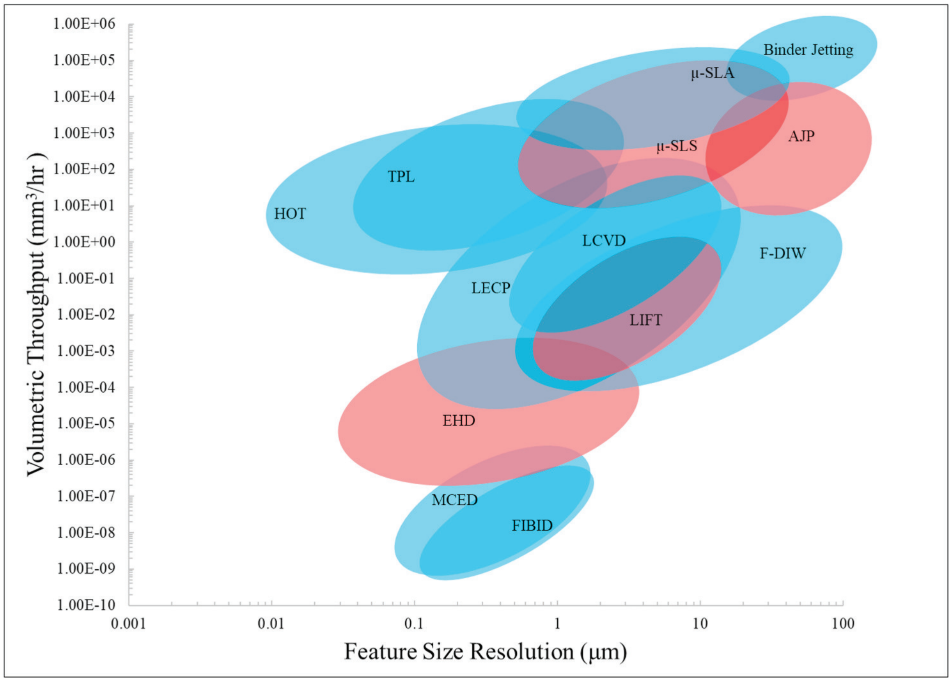

Fig. 1. Chart comparing feature size resolution versus volumetric throughput for different microscale additive manufacturing processes. The blue regions have repeatably demonstrated 3D microscale products while the red regions are currently limited to repeatable 2.5D geometries, and have the potential to be true-3D microscale AM processes. **Abbreviations:** F-DIW – Flow-based Direct Ink Write, EHD Printing – Electro-hydrodynamic Jet Printing, AJP – Aerosol Jet Printing, μ-SLA – Microstereolithography, TPL – Two Photon Photopolymerization/Lithography, LIFT – Laser Induced Forward Transfer, μ-SLS – Microscale Selective Laser Sintering, FIBID – Focused Ion Beam Induced Deposition, LCVD – Laser Chemical Vapor Deposition, MCED - Meniscus-confined Electrodeposition, LECP - Laser-Enabled Electrochemical Printing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The primary material classes that have been explored in the paper are polymers, metals and ceramics. These can be further classified based on raw material state, discretized particle size and morphology, elemental composition, compounding and alloying, deposition mechanisms, and additive and binder content. The concept of microscale AM of true-3D geometries was initially helmed by the polymer microparts (using μ-SLA) [43–45]. While fabricating polymeric microproducts is well within the capabilities of most microscale AM processes given the wide range of flexibility in modifying the material chemistry, careful considerations towards photosensitivity, volumetric diffusion, and initiator design must be made before designing a polymer compound for micro-AM applications. Conductive polymers are being explored widely, because of their compatibility with well-established microscale AM processes (μ-SLA) and their electrical performance.

Metals are also widely explored materials for microfabrication, especially in the microelectronics and MEMS industry. High electrical conductivity, magnetic susceptibility, and mechanical strength are among the several fundamental characteristics of metallic materials which make them lucrative for these applications. Conventional micromanufacturing processes for back-end-of-line fabrication of interconnects mainly uses metals like Al, Cu, Ag, Au, Ni, Ni–Co, and Ni–Fe [46]. MEMS production techniques rely heavily on bulk Si micromachining. Subtractive manufacturing processes for making these microproducts are often highly inflexible, expensive, time consuming, and require complex tooling for microassembly. The development of microscale AM techniques which can process a wide variety of metals and metallic compounds (organometallics, metal salts, alloys, intermetallics) is critical to the growth of the microelectronics industry. Most of the microscale AM technologies that have been discussed in this review have demonstrated the ability to directly process metallic compounds with the exceptions of Optical Tweezing, Micro-stereolithography and Two-Photon Photopolymerization.

Ceramics are another class of materials that have generated a lot of interest in the microfabrication industry because of their higher melting points, corrosion resistance, high hardness/toughness, low CTE, and high thermal conductivity. Various ceramic compounds have been used for fabrication of active and passive electronic components, micro-actuators, microfurnaces, micro-surgical equipment, SOFC chambers, and monolithic periodic structures [47–50]. The primary challenge with ceramic AM is the in-situ particle bed consolidation, which requires highly focused heat fluxes. While the most effective approach is to obtain green parts, which can be sintered in an oven, it limits the design and material space for the ceramic microfabrication.

While the development of material systems is highly dependent on the process physics and fundamental limitations, the following subsections briefly outline the general ideas that can be implemented for improving the material range for microscale AM processes.

2.1.2. *Design for particle size and morphology*

As discussed in the previous parts [23–25], most microscale AM processes use nanoscale particles in a slurry/ink form to avoid limiting the feature size resolution by the size of the particle. The development of nanoparticle systems has grown significantly in recent years due to their potential applications in microfabrication and flexible electronics. One of the key challenges in nanoparticle fabrication is to achieve the required stability of the particles and avoid agglomeration. Particle agglomeration affects the size distribution, which further reduces the part resolution [51,52]. Nanoparticles also have a higher tendency towards oxidation which degrades their performance post consolidation making it necessary to find stabilizing agents and surfactant coatings that can be used to address these issues [25]. As discussed in section 2.2.2 of Part I [24], the ink morphology also affects the packing density and porosity of post-processed parts which has led to bimodal and non-uniform ink configurations that use nanoparticles of different sizes to reduce the porosity in the parts.

2.1.3. *Design for material rheology*

The material deposition mechanisms for microscale AM processes are critical towards achieving the desired part geometry, resolution, and throughput. For nozzle-based deposition processes like F-DIW, AJP, MCED, and Binder Jetting, the resolution and throughput are directly affected by the nozzle size and geometry. F-DIW can print high viscosity inks to create true-3D structures, but it limits the overall throughput of the process [24]. While the electrohydrodynamics of the process shield the EHD process from this limitation, there are still practical trade-offs between the nozzle geometry, ink rheology and resolution. Deposition of high viscosity fluids through smaller nozzles is difficult and may often lead to nozzle clogging. Similarly, coating high viscosity fluids using a slot-die in the μ-SLS process might limit the throughput. CVD-based processes (LCVD, FIBID) and Vat-based processes (TPL, μ-SLA) are not practically affected by the material rheology [23,27]. Therefore, there is a need to co-design the deposition mechanism and material rheology for microscale AM systems to maximize the overall performance characteristics and minimize troubleshooting.

2.1.4. *Design for energy-material interaction*

As in has been discussed in sections 2.3, 3.3, 4,3 and 5.3 of Part I [24], in-bed consolidation is a critical requirement for high throughput fabrication of true-3D geometries in many μ-AM processes. Processes like EHD, AJP, Binder Jetting, and F-DIW must undergo some form of material consolidation of the green part after printing. However, it is difficult to fabricate intricate geometries without structural support (sections 2.3-5.3 in [24]). Therefore, in-situ feature sintering can be employed to impart enough strength to the part as it is being fabricated. Additionally, for direct-energy processes, it is important to understand laser-material interaction characteristics to function in an optimal operating regime. The laser should be able to provide enough energy for the material diffusion [53]. As discussed in section 5.3 in Part II [27], for the μ-SLS process, identifying the laser penetration depth and thermal diffusion length is important for fabricating overhanging structures. The penetration depth limitations are also applicable for μ-SLA. However, in the TPL process, the high photon density at the tip of the gaussian beam converges deep into the vat and leads to the photopolymerization of sub-diffraction features (section 3 in Ref. [27]). This is primarily due to the two-photon absorption physics where the probability of two or more photons getting absorbed by the resin is low, thereby enabling a voxel-based printing at specific locations within the vat. This is fundamentally different from single photon absorption routine followed by μ-SLA, which renders it a layer-by-layer printing process. Laser-material interaction also leads to thermally induced heat affected zones (HAZs), which must be carefully avoided to improve the part quality and surface roughness. The process should be designed with specific understanding of the energy-material interaction, electron beam/laser penetration depths, beam dynamics, particle consolidation efficiency, and HAZ formation.

2.1.5. *Design for multimaterial capabilities*

Multimaterial capabilities could potentially improve part quality, increase volumetric throughput and enable innovative designs. Most of the current microscale AM processes can be scaled to allow for multimaterial deposition capabilities, but it would involve significant development efforts to assess the compatibility of different materials for functional applications [23,24,27]. To understand multimaterial capabilities of a system, a two-pronged approach can be used – material deposition system design and understanding material consolidation. Different deposition mechanisms which would potentially improve the overall process window for depositing multiple materials must be identified. Additionally, the interaction between different materials and its impact on the layer deposition and consolidation process needs extensive experimental investigation. From a bed consolidation perspective, materials which interact with an energy source in a similar manner must be chosen (see 2.1.4).

2.2. *General strategies to enhance True-3D fabrication capabilities*

2.2.1. *Overview of 3D fabrication capabilities of microscale AM processes*

The true-3D nature of AM processes adds significant advantages over bulk-Si micromachining processes as it allows for a wider and an independent exploration of part designs. The fabrication geometry of an AM process is defined as true-3D when the geometric degree-of-freedom is more than 2 and out-of-plane (OOP) features can be fabricated. This implies that these processes must strive towards additively manufacturing at least angled, overhanging, and 'bridge-like' geometries with or without support structures. Additionally, the process must be able to fabricate high aspect ratio structures, which is a major disadvantage of micromachining processes. While most of the processes discussed in this series of articles [23,24,27] have demonstrated some variation of a true-3D structure, only around 50% of them have the capability in their base configuration to repeatably produce these features in a periodic manner (μ-SLA, TPP, OT, Binder Jet, LCVD, FIBID). Processes like EHD, MCED, LIFT, and F-DIW have been slightly modified by the researchers to achieve excellent results fabricating true-3D structures. Phase-change inks and fast-vaporization inks have been used by researchers to demonstrate the true-3D fabrication capabilities of these processes [54,55].

Several researchers have demonstrated angled structures which are essentially less than 90° from vertical to demonstrate true-3D OOP fabrication without support structures; however, the limits to these angles are highly dependent on the material rheology, layer consolidation schemes and feature geometry [23,24,27]. As discussed in section 3.3 in Part I [24], EHD printing has been used to print angled structures but, as seen in Fig. 1, we classify it as a 2.5D process because there are still challenges in achieving these structures with a wide range of materials, and for larger printing windows. A similar argument can be extended to AJP as well. Section 4.3 in Part II [27] shows that although LIFT has been used to print voxels stacked in a bridge-like configuration, but the functionalization of such parts needs further post-processing steps to improve interlayer bonding. As seen Parts II [27] and III [23] figures, processes like μ-SLA, TPP, FIBID and LCVD have consistently been used to fabricate intricate and closed-form structures, and hence they have better, and well-defined true-3D fabrication capabilities as compared to other processes. μ-SLS process has demonstrated 2.5D fabrication capabilities, but there are no physics-based challenges that prevent it from making true-3D parts (section 5.3, Part II [27]). However, the nature of μ-SLS process does not allow fabrication of hollow spherical or closed structures. The fabrication capabilities of these microscale AM process must be evaluated on process specific bases. However, there are some common approaches which have been discussed in the following sections to improve the 3D fabrication capabilities of these processes.

2.2.2. *Design for sacrificial material deposition*

Although design principles for AM processes tend to minimize the volumetric deposition of support structure and maximize their functionality, achieving true-freeform fabrication in AM processes without any sacrificial support material is difficult. Making support structures in microscale AM is coupled with material deposition and resolution challenges (feature-size resolution limited by support structure geometry) [24,27]. A direct implication of the discussion presented in section 2.1 is that multimaterial deposition and consolidation systems can be used to fabricate the support structures made of a sacrificial material which can be thermally removed during post-processing steps. However, designing support structures and support materials that can be easily removed in post-processing remains a key challenge in many μ-AM processes and the currently limits true-3D fabrication in these processes.

2.2.3. *Design for residual stress removal*

Thermal stresses during part formation and heat-affected zones are detrimental to the structural and electrical properties of the parts [48,56]. These thermal stresses form due to the high heating and cooling rates present in many μ-AM processes. In general, thermal stresses can be reduced by using heated substrates or through pulsed energy deposition (ultrafast lasers) [56,57]. Post-processing heat treatments can also be used to reduce residual stresses in metal parts. As concluded in section 3.3.2 in Part II [27], for photopolymerization processes, the resist can be optimized to enable writing at the core of the focal spot, thereby maintaining resolution, as well as voiding any stray polymerization. However, better thermal modeling needs to be done to understand how the processing parameters such as the write speed and the write path in each of the μ-AM processes effect the residual stresses that form in the final part.

2.3. General strategies to enhance resolution capabilities

2.3.1. Overview of resolution limits of microscale AM processes

A comprehensive understanding of resolution limits requires the investigation of the process parameters and physics which affect the spatial and vertical resolution. The resolution of microscale AM processes can be also be a function of other parameters such as the particle size, the fabrication geometry, and the throughput. The true resolution of the process may be affected by high bandwidth particle size distribution [24], complex geometry [24,27], thermal stresses [23,27], HAZs [23,27], and non-optimal process parameters [23,24,27]. Furthermore, the throughput of high-resolution parts is generally lower than for low resolution parts and in some cases might decrease exponentially (FIBID, LCVD) [27]. Nozzle-based processes are generally resolution limited by the nozzle geometry except for EHD [24]. On the other hand, the high resolutions achieved by thin-jet ejections in EHD is limited to a very small process window that varies with the material and the substrate. As discussed in section 4.4 in Part III [23], the wire thickness resolution of MCED also depends on the retraction velocity. Section 5.4 of Part I [24] discusses the issues with overspray degrading the lateral resolution of the AJP process. The spatial resolution of most optics-based processes is limited by the diffraction limit, except for the ones utilizing multi-photon absorption schema [27]. Most laser-based processes report a spatial resolution equivalent to the beam spot size and a vertical resolution based on the deposited layer thickness and the optical and thermal penetration depth. It must be understood that although the theoretical resolutions of several process can be smaller than what has been reported, a strong experimental background is generally missing to prove that these resolutions have been achievable in practice. A comprehensive review of these limits is presented in the respective sections for the processes [23,24,27]. The effect of the process parameters, materials, and throughput plays an important role in defining the practical resolution capabilities of microscale AM process. (Note: one key assumption in defining the spatial and vertical resolution is that the motorized stages used in these processes are not acting as limiting factors.)

2.3.2. Design for reduced focal spot size

The most effective way to enhance the resolution of μ-AM processes is to reduce the focal spot size, either optically or physically, of the writing system in the process. The general approach used in most pyrolytic (for example, laser-based) processes to reduce the focal spot size is to alter the beam profile. As discussed in section 5.4.2 in Part II [27], Bessel-beams have been used to improve the resolution in LECP, and a similar approach can be extended to μ-SLA, μ-SLS, LCVD, and LIFT. Modified optical designs within the diffraction limit can be used for μ-SLS, but the laser-material interaction limits must be experimentally characterized (for visible range and far IR lasers). On the other hand, nozzle-based processes have a limited bandwidth to improve upon the current resolutions, without changing nozzle geometry, which also affects the process throughput. However, section 5.4.2 discusses how aerodynamic lensing has been used in AJP using novel converging-diverging-converging nozzle designs which have improved the resolution by almost ten times.

2.4. General strategies to enhance throughput capabilities

2.4.1. Overview of throughput limits of microscale AM processes

The volumetric throughput of the microscale AM processes plays a major role in defining the economics of the process and leading the production-line integration of these processes. The state-of-the-art throughputs of most of these processes are fundamentally limited by the process physics. For example, the throughput of the LCVD and FIBID process are limited by the thin layer deposition process. The ejection physics of the EHD process defines its overall throughput, where the goal is to avoid the unwanted deposition modes which like overspray and satellite formation. For MCED and μ-SLS, it is important to maintain a stable meniscus throughout the drawing and coating processes, respectively. This varies with the material and process parameters and acts as the primary limits to the throughput.

2.4.2. Design for parallelizing the process

The easiest way to enhance the throughput of most μ-AM processes is to parallelize the feature writing process. Most serial-write laser-based processes can be upgraded to utilize spatial light modulators (SLM) like Digital Micromirror Devices (DMDs) marketed by Texas Instruments. This approach has led to the development of commercial μ-SLA and TPP tools. As discussed in section 5.5 in Part II [27], the throughput of the μ-SLS process is high mainly because of the use of DMD arrays. The same approach can be extended to LIFT, LCVD, and FIBID, although the high laser fluences might damage the micromirrors. A comprehensive failure analysis would be useful for understanding the true lifecycle of these SLMs. However, the cost of these modules is relatively inexpensive compared to the other components of the microscale AM tools. Nozzle-based processes can also be parallelized to incorporate multiple nozzles with multimaterial deposition capabilities.

2.4.3. Design for assembly-line fabrication

The varied capabilities of microscale AM processes can be leveraged to use multiple of these techniques to fabricate different feature sizes and geometries. For example, intricate functional metallic geometries with submicron features using LCVD [23] can be serially added on a structural polymer component that has been fabricated using a higher throughput microscale AM process (like μ-SLA) [27]. Further integration of multiple processes into one tool or assembly line might make it possible to fabricate the less critical features in a part with a higher rate process and then use another process for fabricate features that have specific resolution or materials requirements thus improving the overall throughput of the part without sacrificing part quality.

2.5. Error budgeting and process control

From a precision engineer's perspective, it is imperative to understand that error budgeting, integrated metrology and sensing is critical for ensuring better process control, high-quality microparts and improved throughputs. There are no standard approaches to incorporate these tools within a microscale additive manufacturing framework. However, some general design guidelines must be followed when developing these precision manufacturing frameworks.

2.5.1. Error budgeting

The concept of error budgeting as an analysis tool has been applied in precision machine tool design to predict and control the total error of a machine where it is important to define the accuracy, resolution, and repeatability of the operation [58]. The concept of error budgeting was introduced by Donaldson [59], as a technique to improve the accuracy of diamond turning machines, and later specific design methodologies and approaches were developed by researchers to improve fabrication and measurement tools [60–62]. The key assumptions in error budgeting are: 1. The total error in a specified direction is the sum of all individually propagated errors in that direction. 2. The individually propagated errors can be isolated and controlled. As micro/nano-fabrication processes, microscale AM tool designs must have well-defined sources of systemic and random errors which can be combined to evaluate to the total error of the machine [61]. Without an initial understanding of these errors for a specific design, it is difficult to ascertain whether the errors would be comparable to the desired part resolution, which is a critical requirement for any microfabrication process. Therefore, it is important for a precision design engineer to identify the different kinematic and thermal errors that can exist within the system, analyze their nature (deterministic or non-deterministic) and develop mathematical models to account for them.

2.5.2. Integrated metrology and sensing

Offline metrology for microscale AM fabricated parts can be done using several technologies that have been developed in the semiconductor [63,64], MEMS [65] and meso/macroscale AM [66] communities can be potentially integrated to solve the metrology requirements in microscale AM. The geometric features and surface characteristics of additively manufactured can be measured using contact-based techniques [67] or optical/electron microscopy [22,68,69]. As shown by Saha et al. internal features can be imaged using reconstructed 3D X-ray Computed Tomography (XCT) images [68]. For analyzing the surface topographies of metallic microscale features fabricated using laser-based processes, optical (confocal microscopy, focus variation microscopy and coherence scanning interferometry) and non-optical (XCT) approaches as used by Senin et al. for mesoscale parts can be explored. For AM processes where porosities could be a concern, Mercury Porosimetry can be implemented for understanding the open pore configurations and pore size distributions, while XCT can be used for obtaining both local and global porosity information on the part [70,71].

The need for integrated sensing and metrology is twofold: 1. improve machine and process control 2. Insure repeatable and high-quality products. Integrating machine status feedback using position information [72], and vision-based systems [68,73,74], with advanced controllers [75,76] would be beneficial. Pannier et al. demonstrated a holistic metrology and sensing setup for an in-house EHD printing setup [77]. The transition from open loop/semi-automated research-based machines to intelligent machines has become a necessity to qualify as an advanced manufacturing framework. This is even more critical for a microscale AM tool because of the dimensions at which these are being manufactured and the functionalities expected of them. Real-time process monitoring and control is still an active area of research within the meso/macroscale AM community [78–83], which has conventionally relied on heuristic approaches to improve the process. A shift towards commercialization of microscale AM tool would have to be accentuated by novel process control strategies and learning models.

3. Conclusions

Additive manufacturing technologies have made significant strides in rapid prototyping and development since their conception over 40 years ago. Continuous development in materials engineering, energy sources, system integration, and process design has spearheaded a gradual transition from rapid prototyping to production-scale AM tools. However, the scalability of these processes and tools for microscale fabrication of MEMS devices, sensors, actuators, chip packaging components, biomedical devices, microreactors, and other microscale components has been a challenge for researchers and industry experts alike. Constant demands for miniaturized consumer electronics, life sciences products, and energy-efficient devices, coupled with the fundamental challenges of subtractive Si-micromanufacturing processes, necessitates the search for potential alternative technologies. Emerging additive manufacturing approaches for fabricating sub-100 μm features in microscale products have the potential to address these challenges. The primary factors identified in this paper revolved around evaluating the ability of microscale AM processes to fabricate high resolution, true-3D parts with a potential for scalability. To overcome materials challenges, there is a need to develop liquid phase materials (primarily) for ease-of-deposition and ease-of-processing. These materials can include, but not limited to, metallic nanoparticle inks, conductive and doped polymers, ceramic slurries, and Non-newtonian pastes etc. This paper explored the importance of developing a strong technical framework to study energy-material interaction and co-design them with material rheology considerations, and multimaterial deposition techniques. The inherent design independence and 3D manufacturing capabilities of microscale AM processes have also been explored. The general approach to ensure true-3D part fabrication is to design the process for precise deposition and removal of sacrificial material and avoiding high residual stress concentrations during energy-material interaction. Resolution limits in microscale processes are mainly a function of the material morphology, physical systems and energy-material interaction characteristics, among other restrictions. The general approach to achieving high resolution parts is by reducing the focal spot sizes, either optically or physically. This approach is an active area of research for processes which use laser-based heating and curing and the ones which rely on precise layer-by-layer deposition of material. The final parameter that analyzes the efficiency of microscale AM processes is the ability to scale them up for integration with existing production framework. It is important to understand that several of these processes are active research tools and the current system configurations might not be representative of their scalability potential. With that in mind, the general recommendation for speeding up these processes is to parallelize the primary physical process (like curing, sintering, droplet deposition). This can be achieved by scaling up the equipment and can be complemented by the improving the precision control of these systems. However, some processes are purely rate limited because of the underlying physics (like LCVD, MCED, and FIBID etc.).

However, identifying and developing a single process that has the best capabilities would be difficult, which is true for any manufacturing network. Hybrid approaches to microscale additive manufacturing which combines the best properties of each process must be explored. With the availability of a large amount of data on the processing capabilities of microscale AM techniques, prediction models and simulations can be developed. These can determine the best process that can be implemented in an assembly line of production scale tools for achieving the required resolution and geometry with the desired material. This paper, therefore, is an effort to consolidate the state-of-the-art in microscale additive manufacturing processes and identify the fundamental challenges which are currently impeding the production scale integration of these technologies.

Contributions

All authors contributed to the general ideas that have been presented in this article. DB and MC structured the different ideas into a general format which were presented as design guidelines and edited the rest of the article. The following specific contributions were made in the series of articles on microscale AM processes and their challenges and opportunities.

DB, MC – FDIW, EHD, μ-SLS, 3DP/Binder Jetting, Meniscus-confined Electrodeposition, LIFT, AJP
SC, LS, MP, JH – Optical Tweezing
RH, ZX, RZ - μ-SLA
NR – μ-SLS, Focused-ion Induced Beam Deposition
SS – Two Photon Lithography
RP, SC, LS, JH – Laser-CVD
XZ, SCC – Laser Electrochemical Printing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This series of publications is a joint effort by the members and affiliates of the Micro-Nano Technical Leadership Committee of the American Society for Precision Engineering (ASPE). This work was supported in part by AFOSR under award number FA9550-18-1-0459 and by Prof. Hopkins' DOE-nominated Presidential Early Career Award for Scientists and Engineers under award number B620630. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-JRNL-807723.

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