# Classification of challenges in 3D printing for combined electrochemical and microfluidic applications: a review

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**Abstract**

**Purpose** – The purpose of this paper is to describe, review, classify and analyze the current challenges in three-dimensional printing processes for combined electrochemical and microfluidic fabrication areas, which include printing devices and sensors in specified areas.

**Design/methodology/approach** – A systematic review of the literature focusing on existing challenges is carried out. Focused toward sensors and devices in electrochemical and microfluidic areas, the challenges are oriented for a discussion exploring the suitability of printing varied geometries in an accurate manner. Classifications on challenges are based on four key categories such as process, material, size and application as the printer designs are mostly based on these parameters.

**Findings** – A key three-dimensional printing process methodologies have their unique advantages compared to conventional printing methods, still having the challenges to be addressed, in terms of parameters such as cost, performance, speed, quality, accuracy and resolution. Three-dimensional printing is yet to be applied for consumer usable products, which will boost the manufacturing sector. To be specific, the resolution of printing in desktop printers needs improvement. Printing scientific products are halted with prototyping stages. Challenges in three-dimensional printing sensors and devices have to be addressed by forming integrated processes.

**Research limitations/implications** – The research is underway to define an integrated process-based on three-dimensional Printing. The detailed technical details are not shared for scientific output. The literature is focused to define the challenges.

**Practical implications** – The research can provide ideas to business on innovative designs. Research studies have scope for improvement ideas.

**Social implications** – Review is focused on to have an integrated three-dimensional printer combining processes. This is a cost-oriented approach saving much of space reducing complexity.

**Originality/value** – To date, no other publication reviews the varied three-dimensional printing challenges by classifying according to process, material, size and application aspects. Study on resolution based data is performed and analyzed for improvements. Addressing the challenges will be the solution to identify an integrated process methodology with a cost-effective approach for printing macro/micro/nano objects and devices.

**Keywords** Classification, Challenges, 3D printing, Electrochemical, Microfluidic

**Paper type** Literature review

## 1. Introduction

Additive manufacturing (AM) or three-dimensional printing has drawn enormous interest in recent years. Novel AM processes in micro and macro-engineering applications are developed (Vaezi *et al.*, 2013). Unlike conventional processes, AM processes to fabricate the object by layering material or filament without complex etching, cutting or milling operations. Moreover, four-dimensional printing (Khoo *et al.*, 2015) is evolving in terms of lively functional components using multi-materials. Development of novel high-quality functional materials through effective processes has already evolved and will bring necessary products to manufacturing in the future. As a result, composite materials evolve in varied categories, based on which the processes, customization and product quality lies in. Not to mention, the industrial and academic value of three-dimensional printing has grown.

Further, the sensors, which are in electrochemical areas are manufactured by screen printing (Chang *et al.*, 2009), inkjet (Guo *et al.*, 2017) and e-beam deposition (Martinez *et al.*, 2013) methods. Microfluidic devices use glass, silicon and polymer materials, which are manufactured using micro electro mechanical systems (MEMS). When composite materials, polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), nylon and ultraviolet (UV) resins play a key role for microfluidics toward exhibiting transparency and heat resistance, bio and chemical compatibility is also required with part quality. For example, bio-chemical compatible PolyJet photopolymer associates with Stratasys, which exhibits part quality. Moreover, fusion deposition modeling (FDM), digital light processing (DLP) and stereolithography (SLA) are few of the methods associated with three-dimensional printing of microfluidic devices. Nevertheless, feature resolution and aspect ratios have not matched the photolithographic etching

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methods (Yazdi *et al.*, 2016). The combined use of subtractive and additive technologies could lessen the edge of three-dimensional printing. On the other hand, micro channels are of micro and nano widths, which require varied customized AM methodologies. While dispersion processes would be more suitable for microfluidic specific application prototypes, performance and process factors need to be analyzed and improved.

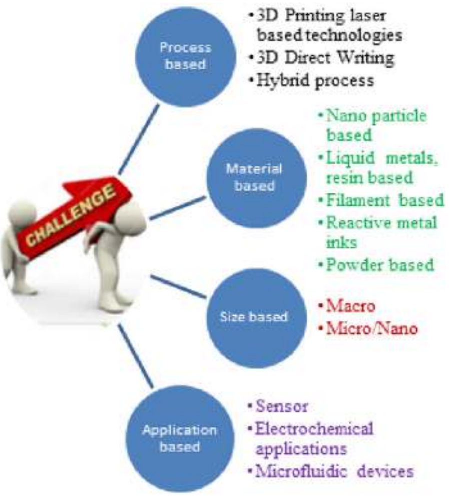
One of the reasons for using the AM process is for the customized geometry designs made to reality with a variety of deposition techniques, which aid in sensor prototypes. However, thin and porous films for which the analyte is to diffuse require compatible techniques and processes. Use of thin layer increases response time in electrochemistry and flow of micro-fluid to dispense and reaction chambers might require complex pathways. Sensitivity has a huge impact on the limit of detection and device resolution, projecting as key performance parameters for sensors. Electroplating, the printing of electrodes, layering of metal particles, spraying and electrochemical depositions require compatibility toward three-dimensional printing processes. Corrosion of material and reactive components needs significant inert pathways. Sensors in these areas requiring better sensitivity response and liquid flows need precision in layering material on a substrate. Therefore, the limitations of existing three-dimensional printing have to be addressed using a strategic way of process integration, motivated by the factors considering current challenges. Integration of mass production for such a combination of sensors would need many changes in terms of high precision manufacturing (McDonagh *et al.*, 2008).

This paper presents a brief review of the key liquid handling AM processes along with classifying challenges in three-dimensional printing fabrication. Classifications of challenges help researchers to channelize the corrective measures. Based on process, material, size, flow parameters and constraints on electrochemical and microfluidic sensors are analyzed for its associated challenges in three-dimensional printing, thereby resulting in a way suggesting for a new integrated process-oriented approach to overcome current challenges.

### 1.1 Classification of current challenges

When AM possess concurrent barriers and challenges, it is essential to classify them according to the existing categories and explore the ways to overcome key issues. AM exists in various forms using fabrication for personal objects and mass production, standardization procedures with intellectual property consistency, multi-material capabilities, scalable and building part resolution. Generally, the build time of an object depends on part size, layer thickness and build orientation. Moreover, the print head determines feature resolution, which is one of the factors determining the part resolution. Other factors are printing speed determined by three axes motors, material feeding rate and material dispensing technique. In the case of ink dispensing, drop size delivered at a particular speed is determined by the type of motor used, ink viscosity and surface tension. In the case of a direct beam, ion beam column performance and a specimen moving system determine resolution (Kim *et al.*, 2012). Laser-based systems provide high resolution based on laser spot size (Gibson *et al.*, 2014). Having said this, the challenges are broadly classified as in Figure 1.

**Figure 1** Classification of current challenges in three-dimensional printing

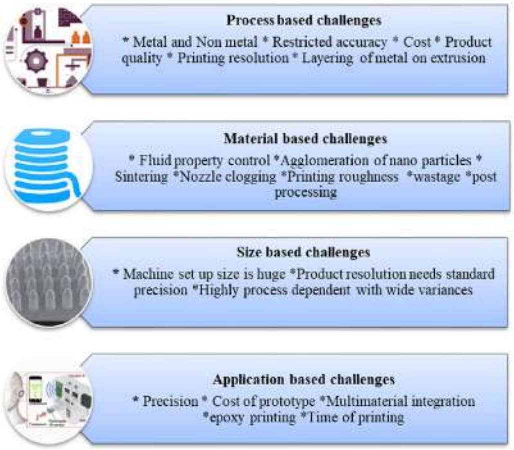


Four types of classifications are made, to consolidate and review the existing challenges. Process-based, material based, size based and application based classifications exist for three-dimensional printing (Figure 2). The three-dimensional printing process flow is defined from computer-aided design (CAD), slicing to hardware operations, the limitations are to be addressed using an integrated workflow.

### 1.2 Process-based challenges

In the present era, defined process wise three-dimensional printing methodologies are reported with innovative material combinations (Kechagias *et al.*, 2008; Hertle *et al.*, 2016; Compton and Lewis, 2014; Khan *et al.*, 2015). Material categories for different AM systems are classified (Singh *et al.*, 2017). In the current scenario, a solid filament that is fed to the three-dimensional printer is melted by applying heat, which is the thermal extrusion process. Filaments of various materials such as ceramics, ABS, PLA, metal composites, wax and much more are heat treated and melted for subsequent layering.

**Figure 2** Highlights of prevailing key issues in three-dimensional printing



Focusing on the microfluidic and electrochemical application printing scenario, the feed material is of liquid type to print metals and chemical combinations. Metals can be in the form of nanoparticle inks and chemicals could be drugs, acetone, silica gel and silicone with high viscosity. Almost, most of the current liquid based AM systems build parts by laser based AM processes such as laser melting or polymerization. Laser melting or sintering happens by placing curable liquid organic resin in a vat, which cures or solidifies under the UV light. Examples of photo curable resins include polyethylene glycol diacrylate microfluidic material, nanofiber epoxy mixture, etc., (Ambrosi and Pumera, 2016). The light cures the resin near the surface to form a thin hardened layer. The next layer is brought inconsequently. There are variations to this technique and depends on the type of liquid resin, type of elevation, optical systems control. Jetting methods involve jetting the drops of liquid photopolymer through a print head and henceforth cures using UV Light. Polymer resins are customized in par with UV radiation exposable energies. Prevailing techniques, which are close to printing fluid/chemical contact devices are analyzed for its working, pros and cons to look for suitable integration ideas to print combined and cost-effective electrochemical and microfluidic devices.

The SLA process takes into account all the sub-processes such as exposure, photoinitiation, photopolymerization, mass and heat transfer (Hayashi *et al.*, 2014). The SLA possesses good accuracy and applies for varied application areas (Castro e Costa *et al.*, 2017; Gao *et al.*, 2015). SLA provides good surface furnish and is better suitable for sensor printing and biological scaffold applications. Various process enhancing methods are available to increase the performance of the SLA process over time, which are shrinkage, tradeoff between resolution and speed, type of lasers influencing the part quality, resolution, etc., post curing is one of the essential steps in the SLA process, as it affects the final accuracy of a rapid prototype. The purpose of post-curing processes is to fully polymerize the uncured resin retained within the structure and to improve its mechanical properties. Under this process, the presence of shrinkage and distortion within the prototype form one of the major sources of error in the SLA process. The amount of shrinkage that is caused during the photocuring process was found to be governed by the process parameters adopted during the laser fabrication process. Post curing might be required to cure the object completely and to ensure the integrity of the required structure (Wong and Hernandez, 2012).

The ProJet series machines are low-cost ones that can produce SLA parts. The photocurable resins are essentially photopolymers and cured using photopolymerization (Xing *et al.*, 2015). There are many types of liquid photopolymers that could be solidified by exposure to electromagnetic radiation, including wavelengths in the gamma rays, namely, x-rays, UV and visible range or electron beam. The vast majority of photopolymers used in commercial AM Systems, including three-dimensional systems, SLA machines that are curable in the UV range. The important component of the building process is the laser and its optical scanning system. The beam comes to a focus on the surface of a liquid photopolymer, curing a predetermined depth of the resin after a controlled time of exposure, which is inversely proportional to the laser scanning speed. The solidification of the liquid resin depends on the energy per unit area deposited during the motion of the focused spot on the surface of the photopolymer. There exists a threshold exposure for the photopolymer to solidify. Again, these systems were pretty costly with huge set up required. It exhibits low surface quality, limiting materials.

DLP (Vatani *et al.*, 2015) and two laser beam technologies (O'Donnell *et al.*, 2017) are variant processes under SLA. The high-resolution micro stereolithography apparatus (MSL) has been developed by using the digital micromirror device (DMD) as the dynamic mask. Similar to the conventional SLA process, the MSL fabricates the complex three-dimensional microstructures in a layer-by-layer fashion. The shapes of these constructed layers are determined by slicing the design CAD model with a series of closely spaced horizontal planes. By taking the sliced layer patterns in the electronic format, the mask patterns are dynamically generated as bitmap images on a computer-programmable array of digital micro-mirrors on the DMD chip (Sun *et al.*, 2005; Espalin *et al.*, 2014).

Stratasys design series three-dimensional printers involve PolyJet prototypes, where they belong to a precision three-dimensional printer. PolyJet three-dimensional printing is more or less similar to inkjet document printing, where instead of jetting drops of ink onto paper, the process jet layers of liquid photopolymer onto a build tray and cures them with UV light. The layers build up one at a time to create a three-dimensional prototype. No additional post curing is required. The support material is printed in the form of gel, which can be easily removed by hand or with water. The layer thickness of 16 m is achieved before moving to the next z layer. The PolyJet system can build thin layers with accurate details depending on the geometry, part orientation and print size. It ensures high accuracy, where precise jetting and build material properties enable fine details and thin walls usually 600 m or less. It ensures fast processing speed with wide material support. While models created by Stratasys systems can be used for conceptual design presentation, design proofing, engineering testing, integration and fitting, functional analysis, market research, etc., post-processing and wastage can be mentioned as a key weaknesses. Further multiJet printing type of processes has wide material restrictions, which are primarily designed for wax casting and polymer printing along with reorientation issue (Snyder *et al.*, 2014).

Thereafter, bio plotter and bioprinting techniques (Yazdi *et al.*, 2016) undergoes a simple process of CAD data handling, dispensing material, and finally, solidification of material to create the structures. Specific 2.5 D CAD-computer-aided manufacturing (CAM) software is used to handle CAD data and process control. The resolution comes to about 1 m for a speed of about 0.1-150 mm/s. The plotting material is first stored in a cartridge and forced to extrude through a small dispensing needle of diameter close to 80 microns into the plotting medium. The solidification of material depends on the material, medium and the temperature control creating the precipitation reaction, phase transition or chemical reaction. The plotting medium involves certain reactions to occur. The solidification is by heating the storage cartridges up to 230°C while the build platform can be heated up to 1,000°C. The system requires a sterile environment as materials include biomaterial, biochemical and living cells. Control of temperature is required to ensure solidification between plotting material and medium by the specific reaction. The key strength is that the user is able to modify process parameters within a specific layer. RegenHUs three-dimensional bioprinting creates tissues or cells, using a bio-ink. Ultimately, product quality and accuracy need improvement with resolution and it is a slow process.

Rapid freeze prototyping (Bang Pham *et al.*, 2008; McDonagh *et al.*, 2008) makes three-dimensional ice parts layer by layer through freezing water droplets. The experimental AM system consists of a three-dimensional positioning subsystem, namely, a material depositing subsystem, a freezing chamber and an electronic control device. The process starts with software, which receives stereolithography (STL) file from CAD software and generates the slice layers of contour information under a command-line interface (CLI) file. Together with a CLI file, further processing of process parameters such as nozzle transverse speed, temperature and fluid viscosity are to be controlled for the fabrication of ice parts. The water line will be frozen by convection in the cold environment and conduction from the previous frozen layer rapidly. Each layer thickness, smoothness is determined by the nozzle adjustment, scanning speed and water feed rate rather than the mechanical mechanism. At the same time, key issues in shape deposition manufacturing (Kruth *et al.*, 1998) originate from temperature gradients caused by fusing molten droplets onto previously deposited layers. Voids are present in the structure.

Principle of FDM is based on surface chemistry, thermal energy and layer manufacturing technology. It builds parts layer by layer by heating thermoplastic material to a semi-liquid state and extruding it. It involves modeling material along with support material, and hence, comparatively a slow process with restricted accuracy and materials. Unpredictable shrinkage can occur due to rapid cooling. Several reviews of the melt extrusion process are reported (Turner *et al.*, 2014; Gao *et al.*, 2015; Vaezi *et al.*, 2013). FDM is a non-laser based process, where the STL file is created in CAD software and sent to the slicer software and the instructions are processed by the printer. Once the machine is activated and the design is transferred, the thermoplastic is heated and melted. The extrusion head releases the material onto the platform. The majority of the systems use thermoplastic materials ABS plastic and PLA. PLA is harder than ABS, which melts at around 180°C-220°C, it possesses higher friction than ABS, which might sometimes make it difficult to extrude. Using PLA might be susceptible to extruder jams. An advantage of using FDM is the lack of expensive lasers equipped in other three-dimensional printing methods or an electron beam of electron beam melting (EBM) process. FDM technology uses less expensive materials and systems, compared to sintering and melting technologies. At the same time, issues such as nozzle clogging, more printing time, material restrictions, lower print quality and poor resolution exist. Most of the printing issues would be poor surface finish, insufficient part resolution. Certain issues (Figure 3) expose nonlinear prints in terms of quality such as warping (Figure 3a), change of dimension over time due to shrinkage, printing errors (Figure 3b) lack of precise layer stack-up (Figure 3c) and finishing. For a fill density of 75 per cent, resolution having 0.04 mm has quality issues (Figure 3d).

Direct ink writing, electro hydrodynamic printing (EHD), laser induced forward transfer (LIFT), electroplating of locally dispensed ions in liquid, laser induced photo reduction, Focused electron/ion beam induced deposition are few of the direct writing methods in microscale AM, which can process metals. If we consider LIFT, it is a two-dimensional metal patterning process. A laser pulse that is focused is absorbed by a metal film coated on a glass layer. It enhances local melting of the metal film by potentially evaporating low melting carriers such as glass. Metal film is a donor in this case. The pressure difference that exists at the carrier-donor interface initiates metal liquid droplet ejection, subsequently transferring the droplet to substrate. Next, the droplet gets cooled and solidifies. For the next droplet to be placed, the carrier is laterally displaced. The complete process is discussed for its principle, geometry, set up, feature size, speed and applications (Hirt *et al.*, 2017).

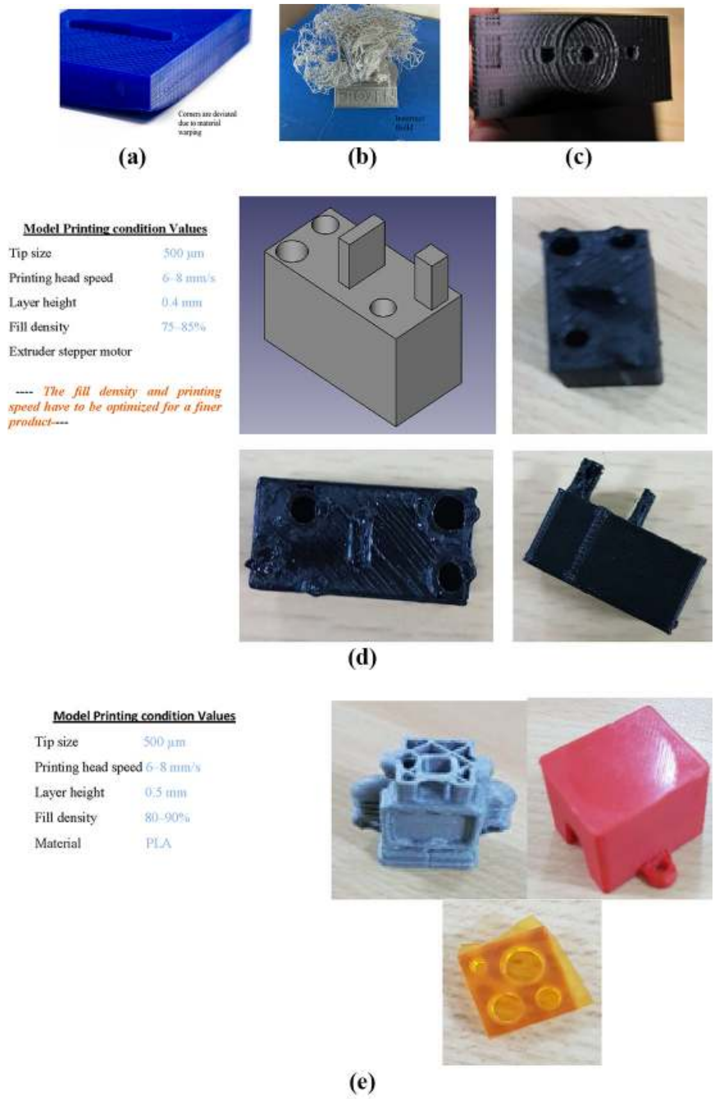
Three-dimensional printing of PLA/multi-walled carbon nano composite dispersions is fabricated using a benchtop three-dimensional printer. Using a 100 $\mu$m syringe nozzle production of free form structures, self-standing structures and scaffolds are obtained. Using a high volatility solvent as dispersion medium, ensures fast evaporation during wet filament deposition and rapid formation of three-dimensional microstructures. At the same time, liquid deposition modeling (LDM) possess limited part geometry, layer resolution. It is rather difficult to operate properly (Giovanni *et al.*, 2015).

While the key printing processes does not support combined features to print electrochemical and microfluidic devices in a single procedural step, it possess improvements in the area of cost, surface finish, quality, temperature handling and printing resolution. Direct writing methods such as LIFT, matrix assisted pulsed laser direct write (MAPLE), laser chemical vapor deposition (LCVD) and LDM use huge power lasers and, in turn, higher electrical consumption. Table I lists the pros and cons of such processes. Many upcoming industries prefer hybrid processes to overcome the challenges posed by AM units. At the same time, using two such kind of methodologies increases unit cost, machine size and production times. Usage of milling and cutting along with AM increases complexity. Standards should evolve for integrated AM process techniques avoiding techniques involving huge laser powers only.

When bulk micromachining, electrochemical, electro-discharge and ultrasonic machining is direct subtractive methods, most of the additive methods discussed above have numerous process methods, hybrid methods were in the intermediate stage. This concept of hybrid systems is very important because customized hybrid processes might be the only way to build them. Including a subtractive component can assist in making the process more precise. Current hybrid processes such as electrochemical fabrication (EFAB), shape deposition modeling (SDM) uses computer numerical control (CNC) milling operation, which adds on both additive and subtractive methodologies.

SDM is an old methodology to fabricate heterogeneous three-dimensional structures. Complex embedded structures such as fiberglass airplane wing, which needs preheating, cooling, forming using sacrificial metal material structures are deployed. SDM integrates material deposition, removal

**Figure 3** Errors in three-dimensional printed objects



**Model Printing condition Values**

| | |
|---|---|
| Tip size | 500 µm |
| Printing head speed | 6–8 mm/s |
| Layer height | 0.4 mm |
| Fill density | 75–85% |
| Extruder stepper motor | |

---- *The fill density and printing speed have to be optimized for a finer product*----

**Model Printing condition Values**

| | |
|---|---|
| Tip size | 500 µm |
| Printing head speed | 6–8 mm/s |
| Layer height | 0.5 mm |
| Fill density | 80–90% |
| Material | PLA |

**Notes:** (a) Warping; (b) incorrect build; (c) lesser product print quality; (d) work piece designed as .FCStd in "Freecad" and three-dimensional printed. Box – length 20 mm; width 10 mm; height 10 mm; pad length – 5 mm; pocket length – 10 mm; material – PLA; (e) three-dimensional printed objects with lesser quality

process operations along with shaping and stress control by shot peening, embed steps. It includes CNC milling and electric discharge machining processes, which makes the technique complex. A high-pressure water wash is required at the end. Undercuts are required for complex geometry. These systems cannot directly fabricate metal shapes and structures (Weiss *et al.*, 1997). A temperature control system is not present. Removing unwanted materials mostly eradicate the AM advantage.

While analyzing in terms of processes, certain aspects are considered for improvements without, which the future developments based on such processes are of key considerations. To consolidate, basic principles include material loading, liquification, extrusion, solidification, positional control, bonding and support generation. To control the material state, maintaining proper temperature is needed (Hofmann, 2014; Zarek *et al.*, 2016). The other approach is by using a chemical change to cause solidification. A curing agent, a residual agent, reaction with air, drying a wet material permits bonding to occur in the later. Table I provides consolidated challenges and possible retrospective measures based on discussed AM techniques.

### 1.3 Material-based challenges

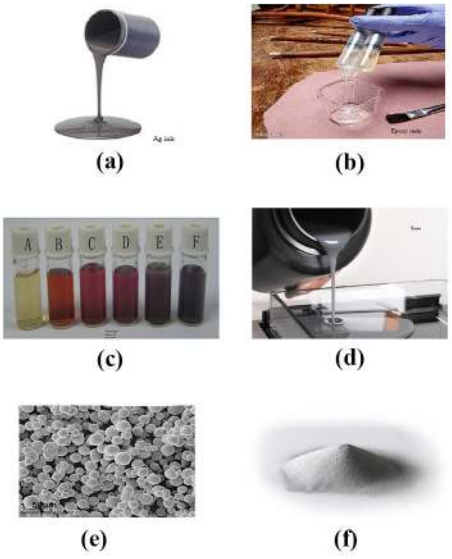
The material can be divided into metals in liquid form, metal nanoparticles and reactive ink form. Often materials are innovated, which suits existing processes (Ribeiro and

**Table I** Process-based AM challenges

| Printing processes group-wise additive technologies (includes metals and non-metals) | Challenges |
|---|---|
| **a. Stereo-lithography**<br>**b. Selective laser Sintering**<br>**c. Selective laser melting**<br>**d. FDM**<br>**e. Laminated object manufacturing**<br>**f. EBM** | Restricted accuracy, unpredictable shrinkage exists (a-e) (Hofmann, 2014)<br>Precise printing resolution required. Unpleasant fumes are present at times (d) (Wong and Hernandez, 2012)<br>Filaments are costly. Certain filaments work tough with the extruder (d) (Dudek, 2013)<br>Conductive filaments are in experimental stage (d) (Hirt *et al.*, 2017)<br>Material wastage due to post-processing and powder (An *et al.*, 2015)<br>Huge temperatures required for melting metals, resulting in a high cost of lasers for specific processes (b, c) (Huang *et al.*, 2013.; Anzalone, 2013)<br>Sintering of powder requires high-cost lasers and post-processing involves laborious effort (b, c, f) (Singh et al., 2017)<br>Cost of machinery is huge (a, b, c, e, f) (Cotteleer, 2014)<br>The layering of metals on extrusion methodologies need improvement for a cost-effective procedure, improving product quality (Singh *et al.*, 2017) |
| **Possible retrospective measure** | Integrating metal and non-metal printing processes by accommodating possible material handling combinations are key to most of the mentioned issues. Compatibility in printing many materials at the desired temperature provides integrated features possible with a cost-effective approach. For example, filaments, powders and viscous liquids could be possibly printed by a single integrated unit with a range of temperatures. To avoid shrinkage and fumes post-processing could be incorporated accordingly. Automating material re-usage can reduce material wastage |
| ***Three-dimensional direct writing*** | |
| **a. Ink based dispensing; aerosol jet**<br>**b. LIFT and MAPLE**<br>**c. Beam deposition methods such as LCVD, focused ion and electron beam direct methods**<br>**d. LDM** | Aerosol serves less for three-dimensional micro-objects (a) (Vaezi, 2013)<br>Optimized temperature requirements are required. The process has a complex set up (b) (Mortara *et al.*, 2009)<br>Direct writing was mainly developed for two-dimensional/2.5 D methods (a-d) (Vaezi, 2013)<br>Complex set up for liquid deposition modeling, limited material handling and printable parts.<br>Layer resolution needs improvement. Not suitable for micro-nano layering (d) (Vaezi, 2013) |
| **Possible retrospective measure** | As the direct energy deposition uses huge electrical power as traditional methods, it is better suited for small production runs. Usage could be minimized. Liquid handling could be part of key three-dimensional printing processes. Use of high power lasers is a key cause |
| ***Hybrid Processes*** | |
| **a. EFAB**<br>**b. SDM** | EFAB uses electrochemical deposition and subtractive planarization for three-dimensional structures (a) (Kruth, 1998)<br>SDM uses CNC milling procedures (b)<br>Hybrid processes combine both additive and subtractive methodologies (a, b) (Waurzyniak, 2007) |
| **Possible retrospective measure** | Hybrid techniques allow high surface finish and dimensional accuracy. This increases the time of manufacturing and cost. Parallel usage of AM and subtractive methods could avoid such drawbacks. Integration of such features into three-dimensional printers based on application requirements would benefit. For example, the aerospace industry requires hybrid processes for product manufacturing. Cost effective machines benefit the industry. Key changes required in the design of three-dimensional printing processes mainly in terms of integration features |

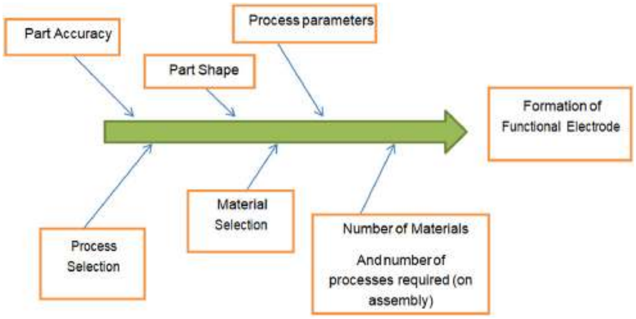
Norrish, 1997; Wong and Hernandez, 2012; Van-Thao *et al.*, 2015), which would belong to one of the mentioned categories with varied fluid properties (Figure 4). Epoxy poses challenges process wise due to its exclusive chemical properties. Prototype materials also include rubber, foam, plastic, viscous metals, waxes, lay brick, metal fiber and binder (Slyper and Hodgins, 2012; Muth *et al.*, 2014). While electrochemical devices require precise metal layers and coatings, microfluidic applications require the appropriate pathway designs in micro dimension sizes. Mechanical part stress possesses greater variance post printing. During post-processing, the support materials for powder-based metal require withstanding heat, cooling and stress variations. The required aspects of fabricating a functional electrode are shown in Figure 5, where part accuracy, shape required process parameters along with the process, material selections determine the efficient printing of any functional electrode.

**Figure 4** Different material categories for three-dimensional printing



**Notes:** (a) Nano silver conductive ink; (b) epoxy resin; (c) colloidal suspension of gold nanoparticle solution containing graphene oxide (Xu *et al.*, 2013); (d) photo-polymerizable liquid resin; (e) ultrafine metal powder (Source: www.purechemflux.co.za/?page_id=65); (f) Ti6Al4V titanium alloy powder (Source: http://hamcc.org/)

**Figure 5** Requirements of fabricating a functional electrode from a printing perspective



Mostly resins, chemical solutions, precursors, and nanoparticle inks fall under the liquid material category. Either in powder or liquid form, the material wastage during fabrication or post-processing exists. Furthermore, the uses of liquid metal as conductors, capacitors and antennas have been demonstrated. While AM is meant for its advantage for efficient material handling in comparison to subtractive technologies, the material wastage should be of key consideration for future improvement. On binder jetting or extrusion, this could be avoided. However, still, the metal processing would need an optimized methodology for temperature handling and direction extrusion mode of fabrication.

Secondly, due to low-temperature processing and better conductivity properties, nanoparticles based fluid materials are getting into the picture. Controls on fluid properties such as viscosity, surface tension and fluid flow parameters to match printing conditions are the need of the hour to suit the existing or customizable processes. While analyzing the nanoparticle-based dispensing, the agglomeration phenomenon is frequently a challenge faced. Certain requirement on surface smoothness differs from product to product for which three-dimensional printing mechanism requires process parameters matching to standards. Also, nanoparticle-based fluid material needs sintering on the surface. However, sintering set-up is part of few process machinery in AM, whereas the hardware restrictions should be overcome for integrated material compatibility. Design alterations are required in extrusion or dispensing methods.

Hardin *et al.* (2015) demonstrated multi-material three-dimensional printing using micro-fluidic print heads optimized for patterning viscoelastic inks. Programmable assembly of functional matter opens up new opportunities in extrusion-based printers. Ota *et al.* (2016) provides a multi-layer schematic of a three-dimensional printed smart object, which integrates advanced IC chips and solid-state components, including liquid-state circuit components and liquid metal interconnects. The process integrates the liquid state printed components with silicon IC chips and multiple printing layers to develop embedded electronic sensing systems. The resolution imposed a major constraint, having a maximum of 300 $\mu$m. In the future, photopolymerization based techniques are expected to adopt an increased resolution for liquid metal patterns.

Three-dimensional modular transfer printing could be used to construct diverse metamaterials in complex three-dimensional architectures to achieve photonic properties (Lee *et al.*, 2016), where the integration of heterogeneous elements to form meta devices is highly desirable. While processing the diverse materials, liquid spreading on printed surface imposes a serious setback in precision, as in inkjet designs affecting spatial uniformities. By modifying the wetting properties, few operational features are available. By combining inkjet and lithography techniques, defined chemical and microfluidic applications could be designed and aimed for increased resolution prints (Coppola *et al.*, 2015; Park *et al.*, 2010). Also, controlling particle assembly within printed patterns are defined for avoiding voids (Onses *et al.*, 2015). Following this powder-based material inks for metallic architectures were demonstrated through thermochemical processing (Jakus *et al.*, 2015).

Lee *et al.* (2017) describes a conductive ink formulation, which exploits electrochemical Zn microparticles in aqueous solutions at room temperature. The resulting electrochemical feature aids for highly conductive antennas, magnetic printed loops and near-field communication devices. Three-dimensional printing arena requires customized solutions to deal with such type of materials.

Processes such as LIFT can handle microstructures, oxidation of metal droplets, whereas maintaining inert atmosphere is an existing challenge. Also, the fabricated structures need to be annealed after controlled nanoparticle paste aging to make it stable. Aging of nanoparticles is required to influence the oxidation state and to determine the required physical and chemical properties. During the aging of nanoparticles, the required structural parameter can be controlled. For example, crystallization on storing metal oxide reduces structural defects on clustered aggregation. Average particle size is controlled (Kuchibhatla *et al.*, 2012). Subsequently, nanopipettes were suggested through meniscus confined electroplating for homogenous surface reaction to fabricate arrays of copper pillars. Following this, the laser-induced photoreduction method relies on laser irradiation of photosensitive metal salt solutions, which initiate local photochemical reduction (Hirt *et al.*, 2017). This reports the two-dimensional and three-dimensional deposition of gold, copper and silver particles for three-dimensional objects. Almost, all the mentioned processes require annealing post printing of metal particles on to a substrate. A significant change of volume upon reduction and oxidation is an issue. Being aware of the microstructural properties of printable material is required for further process improvements. The engineering and protocols for process elements need revision. High material quality, appropriate surface roughness are required though, individual process techniques need integrated approaches to overcome pitfalls.

Microfluidics uses materials mostly like glass, silicon and polymers. Hydrogels, biocompatible materials, polydimethylsiloxane (PDMS), plastics and many more materials are extensively used over the period. Colorless resins containing modified acrylate oligomer and monomer improve microfluidic device transparency. Materials such as nanoparticle inks with varied particle sizes, resins, waxes and epoxies require process modifications for accurate processing. Figure 4 shows a few of its kind. Optimized temperature and material handling mechanisms are yet to be evolved, which will be of multi-material scenarios as applications involve a combination of such types. Whenever the chemical fluid is printed, there is a reactive component or corrosive nature associated. Also, chemical post-processing is required in most of the cases. Nevertheless, electro-deposition might take place affecting the printer extruder and supply. As a result, optimized hardware and design considerations are required for inter-compatibility. Table II summarizes material-based challenge, based on the current scenario in AM-based systems. Organizations have used ceramic mold to print metallic parts, yet the disadvantage of cost and material waste do persist.

### 1.4 Size-based challenges

Micro and nano-objects are evolving phenomena in AM technology. To improve the final printed part, nanomaterials are being used. So far metal, ceramic and carbon nanomaterials are used in SLA, laser sintering, FDM processes. This, in turn, increases the usage of nanomaterials, which will create a few more sets of process innovations for better material and temperature handling capacities. Sintering becomes an inevitable phenomenon for such a scenario, which also increases the final print strength and resolution. Carbon nanotubes and nanofibers bring customized material composites looking beyond laser sintering and direct writing processes. Reducing the machine size along with integrated material handling processes is inevitable. In a laser-based process such as MSL, minimum layer resolution depends on surface tension and viscosity. To overcome this, the two-photon polymerization method uses two photons to release a free radical, which initiates polymerization. The resolution increases considerably as only in the center of laser, ensuring photon strike. Rate of scanning and focusing contributes to increase in printing resolution in processes such as two-photon polymerization. Grain size increases with deposition thickness and scanning speed are inversely proportional to the deposition rate. In surface profile scanning, scanning of the laser beam and scanning in three-dimensional inside the resin result in high resolution compared with layer by layer MSL. In a process such as laser chemical vapor deposition process, the substrate is heated selectively by scanning the laser beam at a rate of 0.5-5 mm/s to dissociate the reactant gas in a selective manner (Vaezi *et al.*, 2013). Malinauskas *et al.* (2012), prototyped nanophotonic lithography for three-dimensional micro/nanostructuring of photopolymers to overcome the issue of laser parameters optimization and for better resolution. Woodpile templates, nanogratings and an optofluidic sensor for lab-on-chip usage were demonstrated. Further focus evolved for stem cell studies and tissue engineering. Through EBM, microstructures of niobium components were fabricated, where agglomeration phenomenon could not be avoided and the process of passing electron beam involves vacuum and high cost for infra-structure (Martinez *et al.*, 2013).

Focused ion beam (FIB), electron-beam and proton-beam assisted deposition methods can achieve structural dimensions as small as a couple of tens of nm. FIB processing involves milling, deposition, implantation and imaging (Kim *et al.*, 2012). Apart from the FIB imaging capabilities obtained by regular scanning of the ion beam, the system can also translate a pattern of doses onto the sample and induce active and controlled surface milling. As a result of the interaction of the ion beam with the sample, milling is a continuous process that always occurs during beam exposure. There are low and high energy FIB applications, which involve ion-induced surface chemistry. It has the advantage of high current density, fine focusing, shorter penetration but still sputtering and etching causes number of working parameters to be in place.

MSL technique is well suited for micro-objects using resins (Leigh *et al.*, 2012). With the evolving scenario of metal printing and production requirement, three-dimensional printing focus is toward printing on a substrate using direct dispensing methods. Nevertheless, the processing parameters are minimized to a greater extent.

Further, the EHD process involves possible evaporation and diffusion of particles outside the substrate, where the loss of material and dispersion is possible (Coppola *et al.*, 2015; Onses *et al.*, 2015). There is an electrical connection exists between the nozzle and printed material, which will cause imprecision. For most of the scenarios, the substrate cannot be made conductive. Ultimately, it has the pros and cons of inkjet type of printing. Table III lists a few key challenges related to the related process methods.

Fabrication of Y-junction microfluidic device through three kinds of AM processes, namely, FDM, PolyJet and DLP-SLA was compared by Macdonald *et al.* (2017). While FDM provides minimum features of $321 \pm 5\,\mu$m, PolyJet could fabricate $205 \pm 13\,\mu$m micro channels. DLP-SLA allows for smallest open channels with better resolution around

**Table II** Materials based challenges for AM

| Group | Challenges in three-dimensional printing |
|---|---|
| **Materials in liquid form**<br>(Hardin *et al.*, 2015; Ota *et al.*, 2016; Lee *et al.*, 2016) | Mostly resins and metals are used in liquid form through most of the three-dimensional printing processes mentioned in Table1. Chemicals, glass wares are of upcoming interest. |
| | Resins have to be customized for its better material properties |
| | More prototypes in required application areas need improvement in material innovations |
| | Material wastage in all terms is not reused. Breakage exists due to incorrect infill |
| | Difficulty in direct extrusion like FDM. Usage of complex nozzle structures, which also charges the fluid. Fluid flow properties and printing conditions require extensive research |
| | Rheological and wetting property needs an extensive exploration before prototyping |
| **Usage of nanoparticles in three-dimensional printing**<br>(Singh *et al.*, 2017; Ivanova, 2013) | Formulation of flow properties should fit the process |
| | Agglomeration of nanoparticles needs to be handled as part of the process |
| | Even though lower melting or sintering temperature is an advantage with a nanoparticle as a three-dimensional printing material, clogging issues might persist on improper handling |
| | Based on particle size, processing procedures vary including the aging process. The process should include the scenario |
| | In the existing processes, inline sintering system for extrusion-based processes is absent |
| | Printing nanoparticles could result in varied surface roughness based on printing speed and extrusion principle |
| **Reactive ink form**<br>(Vaezi, 2013; Wang and Liu, 2014) | Gold, silver and copper reactive inks are normally used and they could react with nozzle or substrate, which requires a thorough corrosion study. Nozzle customization like suitable coatings would be required accompanying suitable chemical post-processing |
| | Electro-deposition might take place, where there is a supply between printed material and nozzle |

**Table III** Size-based printing challenges

| Technology for micro-objects | Challenges while three-dimensional printing |
|---|---|
| **EHD**<br>(Ru, 2014; Khan *et al.*, 2015) | Evaporation and diffusion of particles, where the loss of material or dispersion is possible |
| | Charge connection between substrate and nozzle exists when the printer bed moves as per geometry |
| **FIB**<br>(Kim *et al.*, 2012; Geiss 2014) | Direct writing techniques involve huge and varying temperatures, which also involves either/or milling, imaging, beam overlaps and gas injections. Three-dimensional printing techniques have variants in every application prints |
| **MSL**<br>(Sun, 2013; Macdonald *et al.*, 2014) | Suited for fully micro-objects using customized resins. Printing on a substrate has issues, where most of the applications require |

154 ± 10 $\mu$m with faster processing. The fluidic behavior such as laminar flow performance is similar to current microfluidic devices. Commercial photopolymers is better handled by DLP-SLA. At the same time, PolyJet was able to mass produce microfluidic devices. It is found to be most useful for fabricating complex microfluidic systems including droplet generation and cell culture platforms. FDM has wider material choices such as PLA, electrically conductive composites such as carbon, grapheme etc., the materials are resistant to hydrolysis, polar solvents, acids and alkalis. FDM suits for fabrication of low cost micro mixers. "Suitable printer for the job" with a single or multiple processes and materials to fabricate microfluidic devices compatible to chemical or biological samples is a prevailing challenge.

### 1.5 Application-based challenges

Microfluidic device functions are sample preparation, liquid separation, detection operation and fluid manipulation. Pumps, valves and mixers are device add-ons to help fluid manipulation. Samples are sensed and detected using either electrochemical (potentiometry, amperometry or conductivity), mass spectrometry or biosensor methods transducted and amplified (Ho *et al.*, 2015).

Okandan and co-workers produced monolithic chips with tightly integrated valves, pumps and micro mechanical cell manipulators using micromachining technology. The process exhibits limitations to fabricate flow channels with integrated electrodes using MEMS, which requires manipulation of electromagnetic fields (Okandan *et al.*, 2001) through bulk micro machining etching techniques. Compared to conventional soft lithography, SLA is fast, convenient and cost-efficient (Yazdi *et al.*, 2016). Complicated three-dimensional microproducts in electrochemical areas such as micro sensors, electrochemical energy storage devices, portable detection devices, array of electrodes, devices for electro and bio analysis, deposition and coating techniques if fabricated or printed using AM requires careful process selections. Potentially, these contribute to MEMS, microfluidics and a lab on chip technologies. In the current scenario, selected single process is difficult to suit printing requirements for a functional device (Macdonald *et al.*, 2017).

The microfluidic device is fabricated through multiple steps. Normally a soft lithography is used, which is PDMS casting-based three-dimensional moulding. First, the channel patters are CAD drawn. Next, the channels are moulded on a SU-8 master. The fabricated mould is filled with PDMS, which is cured over 2 h. Once cured, PDMS is removed and cut into required shapes. Oxygen plasma increases strength between PDMS and glass. All these involve manual process and also time consuming. Accuracy is moderate.

The prominent advantages three-dimensional printing offers for microfluidic fabrication over conventional methods include direct additive method of processing instead of multiple steps, fastness in production, innovative designs, cost effectiveness and wide range of materials used. There is no assembly process; instead three-dimensional printing produces in a consecutive series of automated steps. It involves embedding of a tissue scaffold with high porosity, high resolution pore structures in the device and printing biomaterials. Minute three-dimensional structures are layered, which form intricate parts (Ho *et al.*, 2015).

Devices printed in various layer thickness shows that electrodes are printed with very fewer layer heights in terms of z motor movements (Table IV and Figure 6). Combination of chemical and microfluidic is one of the few combined sensor application areas where novel developments are based on, for three-dimensional printing. Considering electrochemical and microfluidic-based sensing devices, material combinations are of varied nature, along with necessary improved processing requirements (Ambrosi and Pumera, 2016; Kamei *et al.*, 2015; Erkal *et al.*, 2014; Lee *et al.*, 2015; Kitson *et al.*, 2012). Automated liquid handlers are required for supply and process of reagents additions, filtration and purification steps, and catalyst mechanisms along with excess gas release system. Processes used for electrochemical include photopolymerization, extrusion, powder-based and lamination technology. Overall, limitations include areas of multi-material, high cost, low yield of production, post-processing additional requirements, mechanical constraints and major design constraints (Wu *et al.*, 2015). Alternate photo-initiators and ability to print materials on the substrate are of interest.

Although newly developed composite AM technologies such as electro SLA process (Pan *et al.*, 2015), light directed electrophoretic deposition (Pascall *et al.*, 2014), copper mixed iron powder extrusion using a unique process (Hwang *et al.*, 2015) have not been adopted for microfluidic device fabrications yet (Yazdi *et al.*, 2016).

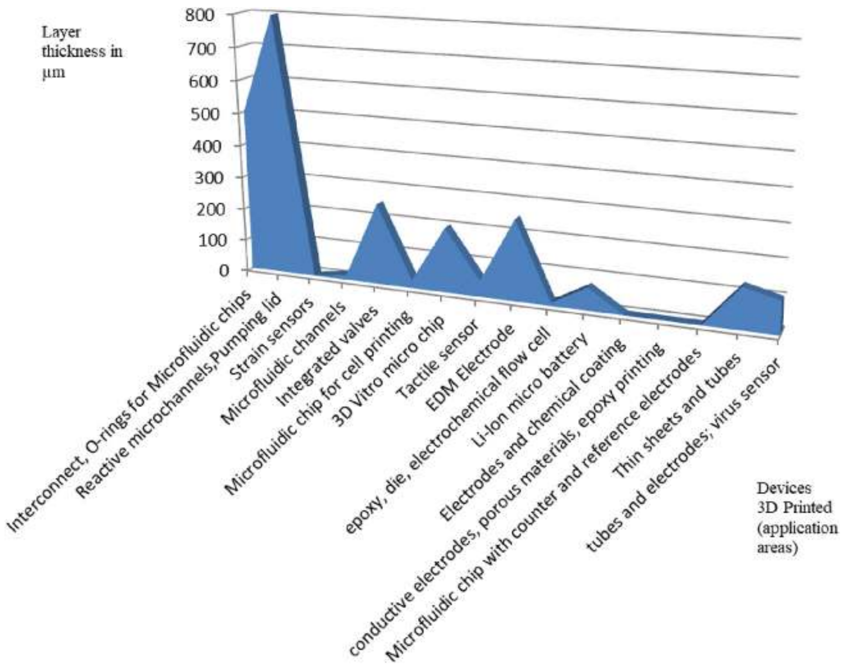
Research studies are reported by Arivarasi *et al.* (2016) on the electrochemical cyanide solution potassium gold cyanide (PGC) being electroless plated through a proposed three-dimensional printing process. The nanoporous gold film is fabricated by immersing copper in PGC, which is tested for surface conductivity. The resulting surface is used for testing heavy metal ions in water. The surface requires specific roughness and porosity for which nano porous gold is formed on copper layer replacing conventional electroless plating. The required porosity on surface is aimed at higher percentage, grain size around 2.5 microns.

Layering of copper ink was prototyped by Arivarasi and team using a spray extruder fitted to FDM machine. The copper particles of 100 nm are coated over silicon substrate having a thickness around 7 $\mu$m (Arivarasi and Kumar, 2017). Normally metals are printed using laser sintering but it is tougher to print on substrates. For a FDM printer to move in precise manner, there is a suggestion by Saldanha *et al.* (2017)

**Table IV** Resolution data-based on material and processing

| Material used | "z" Resolution ($\mu$m) | Device | Process | Multi material |
|---|---|---|---|---|
| **Acrylates and monomers** | 16 | Fluidic device for drug transport (Anderson *et al.*, 2013) | Microfluidic | Yes |
| **Plastic, polymer, polypropylene** | 800 | Reactive micro channels, pumping lid (Walczak and Adamski, 2015) | Microfluidic | Yes |
| **PlasCLEAR** | 25 | Microfluidic chip for cell printing (Waheed *et al.*, 2016) | Microfluidic | No |
| **Resin filled with multi-walled carbon nanotubes** | 50 | Tactile sensor (Vatani *et al.*, 2015) | Electrochemical | No |
| **Copper** | 250 | EDM electrode (Ketchagias *et al.*, 2008) | Electrochemical | No |
| **Adhesive coated polymer, cellulose, plastic and metal** | 10 | Epoxy die, electrochemical flow cell (Gross *et al.*, 2014) | Electrochemical | Yes |
| **Li titanate powder mixed chemical solution** | 70 | Li-ion micro battery (Sun *et al.*, 2013) | Electrochemical | No |
| **Resins** | 0.001 | Electrodes and chemical coating (Calvert, 2001) | Electrochemical | No |
| **Metals (powder)** | 0.01 | Conductive electrodes, porous materials, epoxy printing (Ambrosi and Pumera, 2016) | Electrochemical | Yes |
| **UV curable resins** | 0.001 | Microfluidic chip with counter and reference electrodes (Vaezi *et al.*, 2013) | Microfluidics and electro chemical | Yes |
| **Plastic and metal** | 127 | Thin sheets and tubes (Wong and Hernandez, 2012; Kamarauzaman *et al.*, 2015) | Microfluidics and electro chemical | |
| **PLA** | 100 | Tubes and electrodes; virus sensor (Ambrosi and Pumera, 2016; Ru *et al.*, 2014) | Microfluidics and electro chemical | No |

**Figure 6** Devices printed in various layer thicknesses



and Si-iong and Len (2017) to use piezo walk motor instead of stepper, which results in nano resolution.

For the specific combination of applications, the following techniques are often used: photopolymerisation, extrusion, powder-based and lamination. Mostly the macro size objects with micro meter resolution are prototyped currently (Sun *et al.*, 2013; Zhang *et al.*, 2017; He *et al.*, 2016; Hardin *et al.*, 2015). When it comes to micro and nano-sized features, combining with chemical handling constraints the horizon widens for e.g. MEMS sensors. Limitations such as multi-material handling, high cost, design complexities and low-resolution parts impose a greater roadblock toward obtaining increasing prototypes. Conductive electrodes formed from handling liquid metals and solutions are possible through three-dimensional printing, but with certain process improvements involving heterogeneous combinations.

Erkal with their team demonstrated the ease of integrated electrochemical schemes for three-dimensional printers. They designed microfluidic chips on electrode materials such as platinum, silver and gold. They are added to a threaded receiving port for neurotransmitter detection, measuring oxygen tension in red blood cells, enabling fluid interconnects, membrane insertion to enable molecule detection etc., The detection surface or parts can be printed any number of times if needs to be reused (Erkal *et al.*, 2014).

EDM electrode was three-dimensional printed (Kechagias *et al*, 2008). Possible variations were also listed comparing original shape. Au *et al.* (2015) used a binder jetting three-dimensional printer to create plaster block. This created a porous surface, which was post-treated with epoxy resin for hardening. Printing conditions play a vital role to avoid further chemical treatments post printing. Further sealed reaction ware device was fabricated keeping in mind the reaction sequences, volatility, sequence, automation and filtration of required materials (Kitson *et al.*, 2013). Re-configurable chemical tools are of interest using FDM type of model. In a similar context, multifunctional reaction wares were designed containing a solution holding chamber, mixing and reaction chambers fitting with a camera (Symes *et al.*, 2012). This work posed initial set up toward optimal engineered set up resulting in an integrated design.

FDM commercial printer “Profi3D Maker” was used in a study to print ABS microfluidic chip for bacteria deoxyribonucleic acid (DNA) detection. The goal was to isolate microbial particles such as whole bacteria, cells, oxygen and other biomolecules to prevent infection taking place. The device consists of reaction chamber, two channels and a dosing capillary. The temperature sensor, fan and heating element were placed in a thermostatic box inside the chip. Gold nano particle surface is capable of binding to target DNA site, the mecA gene. MecA gene is the specific gene of the MRSA bacteria, which gets detected and amplified. Colorimetric analysis of the outcome of mecA gene and gold nanoparticles detects the bacterial presence. The device is printed with specific primers on the chip (Ho *et al.*, 2015). At the same time, if the surface is of metal say, for environmental analysis, FDM may pose a challenge. FDM can print composites, plastics and many more filaments with low range temperature operation.

Inkjet printing of microfluidic devices demonstrated ways toward integrating with chip structure (Walczak and Adamski, 2015). Also, few works are reported by Anderson *et al.* (2013) for an integrated fluidic device. Pumping lid method enabled by multi-material three-dimensional printing combines both elastic and rigid type of materials (Begolo *et al.*, 2014). Pressure and flow rates were evaluated for the model and validated. Using multiple lids or a composite lid with different inlets enter through automated pumping.

Three-dimensional printing microfluidic devices for sensor systems are still evolving phenomena, having resulted in noted reported works (Hardin *et al.*, 2015; Yazdi *et al.*, 2016; Kitson *et al.*, 2012). Applications include bio-research, pathogen detection, point-of-care diagnostics, tissue engineering and multiphasic screening. More on sensor, electrochemical and microfluidic applications are listed (Table V), listing major process requirements in terms of effective fluid handling, errors correction, resolution improvement and multi-material improvements. Design of systems involves more research toward integrating both fields.

Farré-Lladós *et al.* (2016) prototyped micro channels suitable for high operation pressures micro particle image velocimetry circuit using rapid prototyping printer. The device would be capable of handling even complex fluid such as grease. Material used was PDMS and polymer with young modulus starting 360 kPa. The novel three-dimensional printer method can manufacture high pressure micro channels, subsequently sealed using glass slides with ultra violet curable glue. In this case, micro-channel and hydraulic hose connection is manufactured as a single integrated part using Stratasys three-dimensional printer. The printed microchannels could withstand pressures up to 5 Mpa without leakages.

An integrated porous membrane and embedded liquid reagents was prototyped by multi material three-dimensional printer to analyze nitrate in soil. The commercially available composite filament was turned into a porous material through dissolution of a water soluble material. Before sealing, liquid reagents were integrated by pausing the printer. Three different FDM filaments, namely, 1.75 mm PLA, clear ABS and Lay Felt were used. Here each device is used only once to avoid analyte adsorption and fouling.

Yang *et al.* (2016) prototyped silver microelectrode arrays (Figure 7) with three different electrode spacings, which were fabricated by three-dimensional printing through aerosol technology. Printed at a length scale of 15 m spacing, work established the lower limit of the microelectrode. While the direct writing method is chosen for such application, a combination of aerosol method applying sheath gas, carrier gas and the atomizer is synchronized for the X-Y stage. Comparing to the current scenario, three-dimensional printing involves Z-direction movement, which needs further design improvements to accommodate micro and nano layering of metal particles on the substrate. The analysis of the literature reveals the improvement in printed resolution. The trend is plotted reference wise in Figure 8.

Three-dimensional printing technologies are discussed by Ambrosi *et al.* (2015) where conductive electrodes used for redox and catalytic processes can be manufactured. Liquid handling systems such as voltammetric cells or microfluidic systems can be integrated with the electrode. A paster based block fabricated by Czyżewski resulted in a porous surface, post processed by epoxy resin (carbon nanofiber) to harden the structure. As the next development, graphene is used in filament form for printing. Another SLA-based electrochemical printing experimentation was carried out by Snowden *et al.* (2010). Subsequently, Krejcova and Erkal *et al.* prototyped PLA-based microfluidic chip to detect influenza virus. Bishop *et al.* (2017) fabricated a microfluidic device using FDM method and used synthesis of Prussian blue nanoparticles and a sensing system to detect hydrogen peroxide. The process used an integrated gold surface sensing electrode.

Kamei *et al.* (2015) applied soft lithography mold process in three-dimensional printing for the fabrication of three-dimensional micro channels toward applications of tissue engineering. Cell-based assays using poly dimethyl siloxane castings are fabricated (Figure 9). Much of the post-processing tasks and assembly takes effort.

## 2. Need for approaches toward process integration

For any sensors or actuators application, integrated components from various AM processes are important, which case it exceeds the normal prototyping cost and effort estimates. Considering the sensor parts to be three-dimensional printed in the areas of electrochemistry and microfluidics, the design approaches addressing pitfalls, needs thorough analysis. CAD/CAM design methods were originally developed having two-dimensional in mind, whereas micro dimension complex designing needs refinement for practical printing considerations. In spite of the hype three-dimensional printing has received till date, certain key issues are ignored say., shape optimization through design software, fill density, designing micron cell and tissue structures, algorithmic topological optimization improvements. Pre and post processing need a thorough optimization particularly in support creation, porosity generation, tessellation and geometry errors. Multimaterial aspects would require a redesign of layering structures right from hardware components to software preprocessing methods.

Subsequently, the material combination and usage of nanomaterials require appropriate material supply mechanism. Syringe usage needs a standardized form receiving material supply accommodating FDM hardware. In the current scenario, when material changes often the machine design changes, for which design software bear ultimate product ideas. Three-dimensional process mechanisms need compatibility for handling multiple material and application portfolios.

Metal processing is slowly moving from powder-based to FDM-based methodology. Numerous filaments having composite combinations of metal and plastic with conductive nature are available commercially. Yet, the process could leverage the innovative signs for improvement. Processing powder produces material waste along with post-processing. High power lasers induce more material cost. While integrating with other simple three-dimensional printing processes, the mentioned limitations will bring more consumer required products being three-dimensional printed for mass manufacturing, and hence, economic leverage.

Suggestions include less printing errors, which might be from CAD, slicer and hardware sources. Increasing material handling compatibility is a key re-organizing scenario to be considered for the integrated process approach. The material in the form of powder, solid, liquid, and filament has to be integrated to some possible level so that sintering and laser could be made optional when essential. Incorporation of sintering system in sync with syringe holders should be possible

**Table V** Application-based challenges for AM

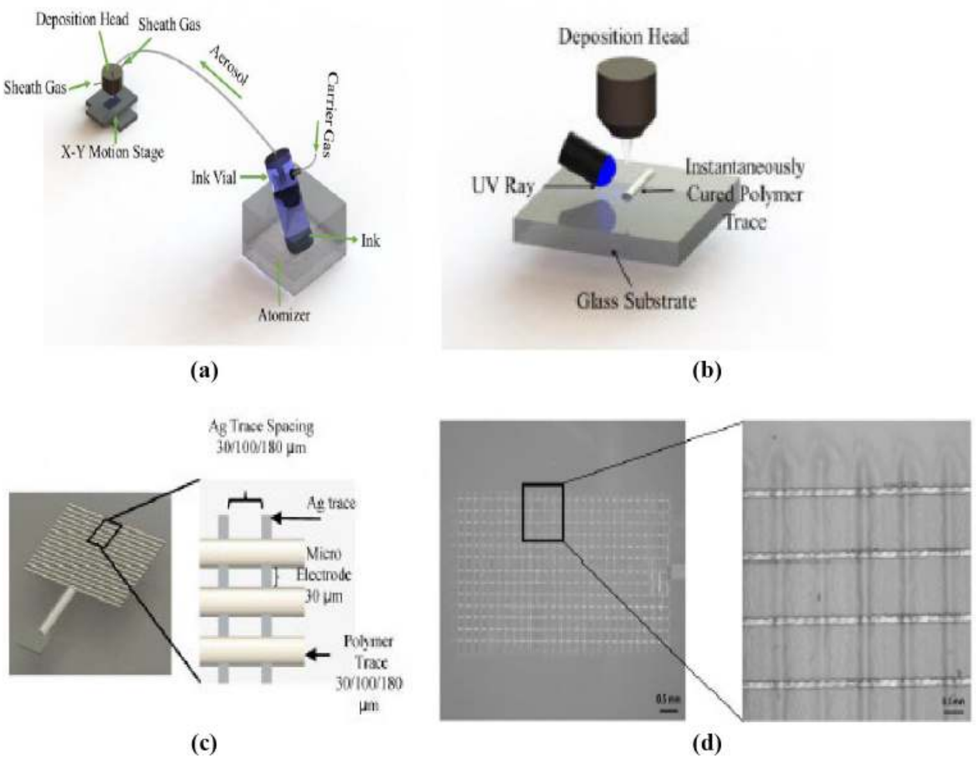
| Application | Challenge |
|---|---|
| **Sensor applications** (Vatani *et al.*, 2015; Shemelya, 2013; Vatani *et al.*, 2013) | Printing resolution needs improvement for FDM-based micro prints<br>Metal printing on a substrate requires cost-effective process using an integrated approach<br>Film formation on a substrate requires precise resolution of deposition, whereas the AM technology has to be made comparable to other technologies like e-beam and metal spraying techniques. They involve vacuum or evaporation techniques, which is more costly.<br>In AM systems few aerosol methods used are complex and costly. Material is handled through vacuum operation<br>Molds and frames are required for printing sensors. Mostly powder-based technologies are used for metal-based sensors. Multi-material printing aspects are considered for design innovations |
| **Electrochemical applications** (Ambrosi and Pumera, 2016; Bakker 2006; Vaezi, 2013; Ivanova *et al.*, 2013; Hirt *et al.*, 2017) | Three-dimensional printing of metal electrodes such as platinum, conductive copper, and gold electrodes is challenging<br>Mostly layering metal using cost-effective means needs more research and prototypes<br>Sample handling with oxidation and reduction potentials is of significance<br>Integrated reaction wares with software for chemical processing and printing is yet to evolve<br>Printing conditions for process specific variables, conditions require a framework<br>Complex design methodologies are in place. Prototypes are not yet commercialized like seen for other few sensing products |
| **Microfluidic applications** (Macdonald *et al.*, 2014; Yazdi *et al.*, 2017; Farré-Lladós *et al.*, 2016) | PDMS molding for post-treatment is tough. Variations in AM processes are required often.<br>Limitations in material properties and surface finish have to be overcome<br>Peeling issues persist. PDMS is not currently used in three-dimensional printing due to slow polymerization and solidification property<br>Channels less than 50-100 $\mu$m is tough to be three-dimensional printed. Improvement in resin property is required<br>Hardware modifications necessary (SLA-based)<br>Preparation of customized resin is time-consuming. A mostly hybrid type of printing is possible<br>Varied surface roughness post-printing<br>Transparent materials are tough to be processed. Optimization in design, hardware and processing steps<br>While macro and millifluidic (flow channels $>$ 4 mm) is easily possible to be three-dimensional printed, microfluidic types have constraints such as increasing connectivity, in-situ reactions designs, temperature control, solvent compatibility, etc., |
| **Combined electrochemical and microfluidic applications** (Yazdi *et al.*, 2016) | Evolving metal mixed filaments could be used for combined applications<br>Integrated printing approach combining materials and current processes enable wider reach and marketing. In other words, increased material handling capability in a single machine<br>Incorporation of syringe dispensing along with sintering capability for nanomaterial printing could be materialized<br>Integration around FDM process increases cost effectiveness<br>FDM resolution is not suitable for micro or nano micro fluidic feature parts and has rough outer structures<br>In spite powder-based processes provide high resolution, removal of the excess materials for internal microfluidic channels make the technique unsuitable<br>Project HD machines produce less resemblance shapes to normal objects. Vertical to horizontal orientation is bad (Yazdi *et al.*, 2016) |

for metal printing through desktop systems. Material wastage is lesser in FDM-based dispensing process. Hereby, process integration requirements (Figure 10) could optimize the way three-dimensional printing scenario extends toward the future.

## 3. Summary and conclusion

To conclude, an overall review of current challenges is performed and classified for further optimization areas. Process, material, size and application-based challenges are charted out for further clarity in addressing through an integrated approach of processes. While process definitions involve design, slicing, hardware and application-based on size, based on printed objects, further refinement requires for an integrated approach, which would address challenges discussed. While the integration technique could be proposed to be designed around FDM, which is a cost-effective process, sintering could be preferred with simple photonic sintering instead of high power lasers for small size applications. Usage of high power lasers even for smaller

**Figure 7** Schematic showing the fabrication process for microelectrode arrays using an aerosol jet printer (Yang *et al.*, 2016)



**Notes:** (a) Aerosol printer schematic; (b) aerosol printer: closer schematic; (c) schematic of microelectrode array; (d) image of printed array

**Figure 8** Improvements in print resolution through literature references

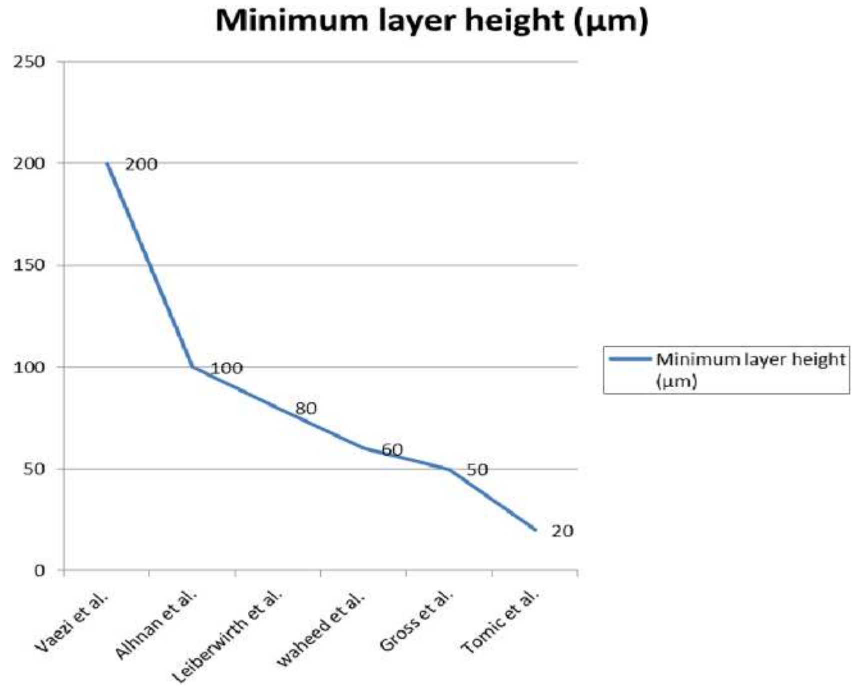
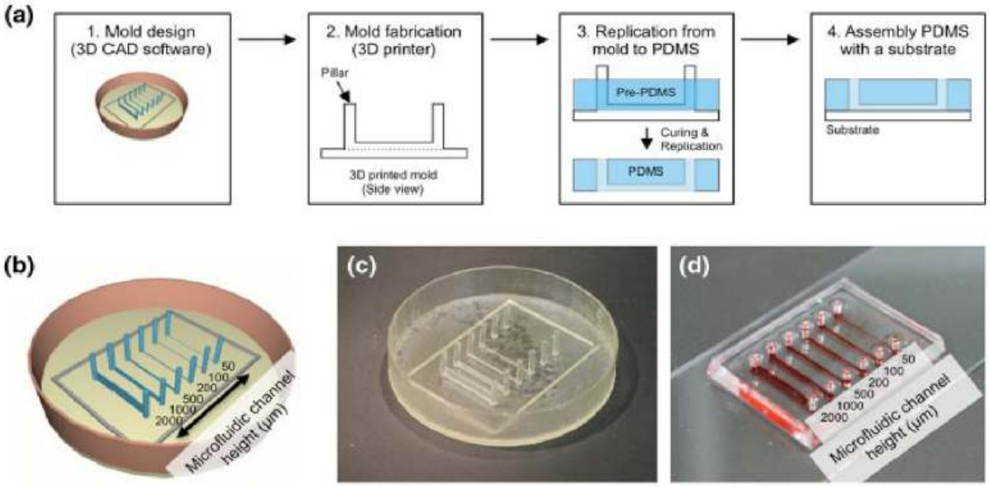
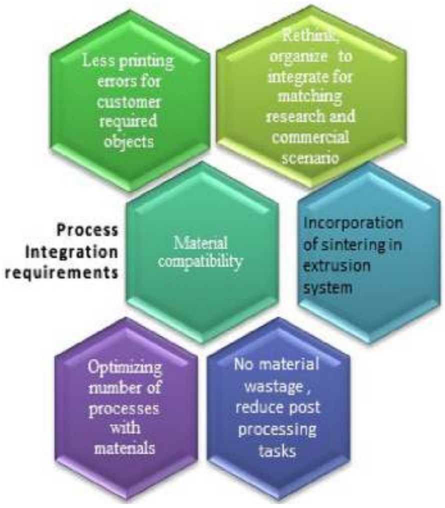


**Figure 9** Micro channel fabrication example



**Source:** (Kamei *et al.*, 2015)

**Figure 10** Process integration requirements



applications could be avoided using such an approach. Techniques of handling extruder jams in FDM can be enhanced by additional designs such as supportive pathways at specific points during extrusion. Material fabrication needs to provide improved melting properties or temperature handling to avoid jams. Increase in resolution can be obtained by alternate precise motors instead of steppers that are used currently. Quality of printing should be increased by proper selection of material, motor speed, the optimum scanning speed of lasers matching materials, etc. Application of three-dimensional printing to microfluidic and electrochemical device fabrications will enhance their use as portable diagnostic tools in limited resource requirements and enhance future research. Together with the exploration of mentioned areas and analysis followed by design prototypes, outlines for promising future work.

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