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Additive Manufacturing (3D Printing): A Review on the Micro fabrication Methods

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Abstract: The advent of Additive Manufacturing or 3D Printing has led to a revolution in manufacturing sector providing high flexibility in customization at the consumer level and also serving as an efficient tool for further research and development. The highlights of 3D Printing including rapid prototyping, freedom of design and minimal waste generation have led to the acceptance of Additive Manufacturing (AM) as a viable method for mass production for 3D microstructures with high aspect ratios and fabrication of 3D assemblies. A comprehensive review and classification of the major 3D Printing techniques into three broad categories: Scalable Micro-AM systems, 3D Direct Writing and Hybrid processes has been done. Overall, this paper provides an overview of current state of methods of 3d Printing and scope for future research and development.
Keywords: Additive Manufacturing (AM), 3D Printing, scalable Micro AM, Direct Writing (DW), hybrid processes.

I. INTRODUCTION

The new generation of the microproducts possess complicated 3D microstructures and are made from a wide variety of materials to perform their specific functions. 3D Micro Additive Manufacturing (AM) techniques have the ability to produce 3D microproducts having complicated geometries with specific functionality and involve the utilisation of a diversity of materials as compared to other traditional micromachining or lithography based methods [1]. These have been broadly classified into Scalable Additive Manufacturing, 3D Direct Writing, Hybrid Process.

The microproducts can be of three types, Micro Electromechanical Systems (MEMS), Micro-Opto Electromechanical (MOEMS), Micro Electronic Products and Micro-optical Electronics System (MOES), depending on operation fundamentals and product applications [2].

The latest miniaturization drive of the products in the especially in the optics, medical, biotechnology, automotive and electronics sectors have caused a huge demand for developments in micro- and nano- fabrication technologies and their integration in the latest manufacturing platforms [3]. A wide range of micromanufacturing or microfabrication technologies have been introduced each with its own set of specific capabilities and applications depending upon their fundamentals; and it has augmented several classification techniques suggested by various researchers. Masuzawa [4] classification focused on micromachining processes on the basis of the machining operation implemented. Madou [5] categorized the microfabrication processes as lithographic and non-lithographic techniques. While Brousseau [6] and Brinksmeir [7] provided a classification in which it is classified into two generic technology groups; first the Microsystem Technologies (MST) which encompasses the process of manufacture of MOEMS and MEMS. And second, Microengineering Technologies (MET) which is on the basis of processes utilised in the manufacturing of moulds, micro-structured surfaces and highly precise mechanical components. Whereas, Dimov et al [8] suggested an alternative classification which is based on the basis of material relevance and process "dimension". It can be further classified into MEMS and non- MEMS manufacturing [9]. MEMS Manufacturing includes lithography, laser ablation, photolithography, plating, chemical etching, electroplating and moulding (LIGA) etc. Whereas, Non -MEMS Manufacturing compromises micro-extrusion, laser cutting/patterning/drilling, microinjection, EDM, moulding, microstamping, micro-embossing, micro-mechanical cutting [2]. Microfabrication techniques have also been classified into silicon based and non-silicon material micro-fabrication, depending upon the materials used.

There have been major improvements in development of micromanufacturing techniques which can be used in the production of geometrically complicated 3D microstructures having sufficiently higher aspect ratios which utilize a wide variety of materials. The development has found utilisation in the production of microdevices which have played a crucial role in the evolvement of modern technology and its functional applications such as MEMS, photonic crystals, biochips, micro-fluidic devices etc. [10,11], micro-optical instruments, medical devices and integrated microsensors. Some manufacturing methods like soft lithography [12], laser photoablation [13], localized electrochemical deposition [14], the LIGA process [15,16], which were initially developed for production of 2.5D microparts have been further augmented by various researches to enhance their ability to produce more complicated microstructures. Electrochemical Fabrication (EFAB) has been established for the production of geometrically complicated 3D metal devices and microparts in a layer by layer deposition manner [17,18].

The present day microfabrication technology's capability for true 3D micro manufacturing was enhanced with development of Micro-additive manufacturing (Micro -AM). Multi-layered Lithography [19], Deep Proton Writing [20] and layer by layer based AM processes were the earlier attempts towards true 3D microfabrication. Methods of AM have been developed with a special focus on meeting the latest demands in the field of complex 3D structures having fine resolutions. The ability to fabricate larger structures, reduction of printing defects, enhancement in mechanical properties and rapid prototyping are the key objectives of AM technologies [21].

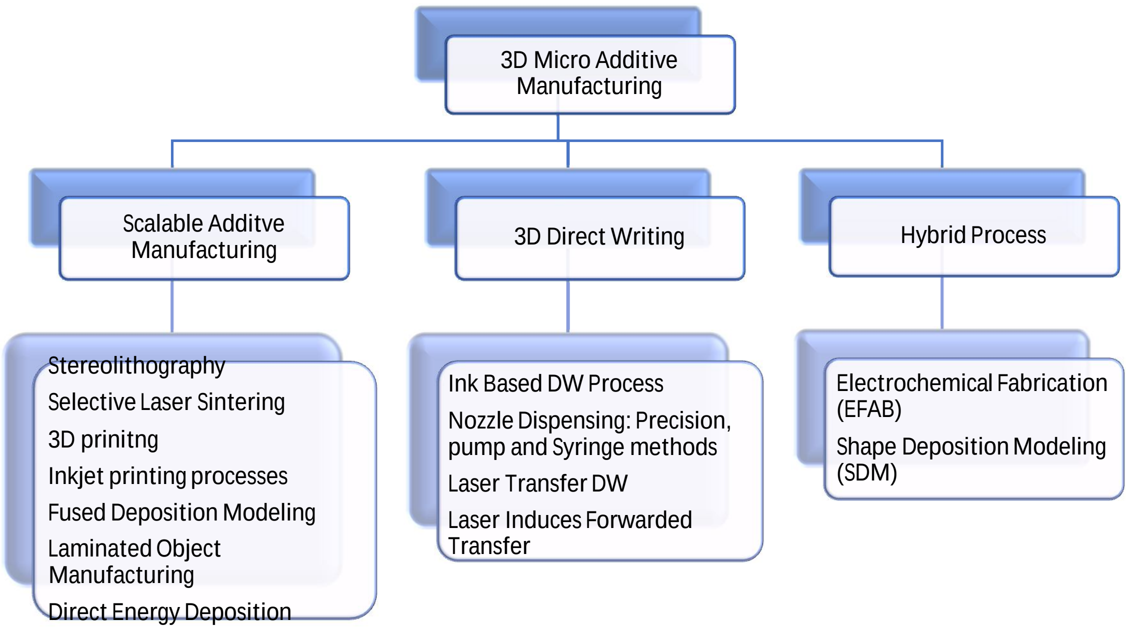


Fig. 1 Description and Classification 3D Micro-AM [1]

II. SCALABLE ADDITIVE MANUFACTURING TECHNOLOGIES

The techniques included in the Scalable AM Technologies are the first group of technologies which have been seen as a viable approach for true 3D microfabrication and can be utilized efficiently to produce complex 3D micro-components/assemblies. These have been widely utilized within a decade for production on both macro and micro scale. With an exception of micro-stereolithography (MSL) this class of micro AM in general faces certain difficulties in microscale fabrication as these have been primarily developed for normal size manufacturing. Apart from this these processes are limited due to its temperament both for micro and normal size manufacturing.

A. Stereolithography Processes (SL)

It was in 1986 when 3D Systems Inc developed SL as a first commercial AM process utilizing layer-by-layer polymerization of photosensitive resin using electron beam or ultraviolet (UV) light. The monomer solution or resin are mainly acidic or epoxy based. After the polymerisation of pattern made inside the component, the layer of resin is then solidified to impart sufficient strength to bind the subsequent layers. Certain post processing treatments including photo-curing or heating can be effective in enhancing the mechanical performance of the printed parts. Ceramic polymer composites [22] can be printed by monomers enriched with a dispersion consisting of ceramic particles or ceramifiable monomers like silicon oxycarbide [23]. High quality parts can be printed by it at a fine resolution of 10µm [24]. Figure 2 below describes the SL process.

Ikuta and Hirowatari [26] introduced MSL by developing SL improved super IH process and integrated hardened (IH) polymer [27]. Scanning MSL and Projection MSL have emerged as two broad MSL Techniques depending on different beam delivery system. The scanning technique involves the solidification of the photopolymer (including, UV photo-initiator, monomer and other additives) in a point-by-point and line-by-line manner in each layer and hence earning the name "vector-by-vector" MSL. It is essential to maintain short laser focal length to achieve micrometres sizes laser spots.

The complete curing of the photopolymer layer in a single exposure through the mask provided, saved a significant amount of build time in projection MSL as contrasted to scanning MSL yet the first generation of projection MSL setups were costly and slow due to the need for the production of large number of projection masks. Further developments lead to the usage of dynamic masks which omitted the need for frequent replacement of mask after each layer of deposition and allowed for electronic pattern creating [1]. In 1997, Bertsch *et al.* [28,29] proposed the usage of Liquid Crystal Display as dynamic mask for controlling and creating the desired pattern of each layer in the projection SL process. Apart from cost reduction the usage of LCD Projectors also reduced the difficulties emerging from the glass mask alignment. But the inclusion of LCD mask projection brings its own set of challenges like; low filling ratio, large pixel sizes, low stitching speed (~ 20ms), higher optical density during the on mode and low optical density of the refractive elements during the off mode [30]. The larger pixel size of the developed parts and other aforesaid defects restrict the scope for subsequent improvements in the field of micro-manufacturing. MSL technique is employed successfully in various fields, including micro sensors and micro machines [31], microfluidic systems [32], optical waveguides [33], 3D photonic band gap structures [34], fluid chips for protein synthesis [35] and bio-analysis [28,29].

1) *Advantages:* MSL is quite suitable for microfabrication owing to lesser porosity, good surface quality and higher resolutions offered. They are found to be highly suitable for micro manufacturing of complex nano composites.
2) *Drawbacks:* In MSL systems the surface tension and viscosity of the resin limit the minimum thickness of the deposit layer. To overcome this, two-photon-polymerization (2PP) method was developed which employed a mode locked Titanium-Sapphire laser that emits at 770nm. Two photons are needed to release a free radical for initiating polymerization in 2PP process. Two broad scanning techniques are used in 2PP process namely surface profile scanning and rastor scanning. In surface profile scanning, the laser beam is focussed and scanned in 3D within the resin chain producing higher resolutions in contrast to layer-by-layer MSL process [36]. 2PP process has been successfully applied in the microfabrication of micro-rotors [37], micro-oscillators [38], optical memories [39] and photonic crystals [40,41,42]. A hybrid process has been introduced, which include an additive two-photon caused polymer curing process and a selective ablation subtractive process, in which the limitations of 2PP process have been removed using selective ablation- assisted 2PP technique. New photo-initiators have further enhanced the sensitivity of the two photon process resulting in synthesis of better quality microparts [43,44].
3) *Recent Advancements in Projection MSL:* Bertsch's research group [45] proposed the idea of using high resolution Digital Micromirror Device (DMD) which are embedded in Digital light processing projectors, as dynamic mask in MSL process. The group utilized optical filters and a metal halide lamp for selection of appropriate visible wavelength band to iridate the resin. The inclusion of Enhanced Resolution Module (ERM) in DMD based MSL systems can improve the achievable resolution. The Perfactory is an example of a DMD based micro-SL System supplied with ERM. This system is capable of building 3D microparts of pixel size as low as 30µm in a layer-by-layer manner using ERM module. Rapid Micro Product Development (RPMD) technology is another Projection MSL technique, which uses parallel laser beams [1]. RPMD mask is a combination of mask technology employed in photolithography and RPMD, which results in a considerable reduction of exposure time and permits for exposure of larger areas of the layers. With the use of RMPD nano face technology [46] it is possible to produce microparts with higher resolution and better surface quality. The great applicability for fabricating geometrically complicated 3D microsystems and microparts displayed by this micromanufacturing technology have served as a motivation for more research in dynamic masks. Various attempts have also been made to expand the range of raw materials used in MSL process for production and fabrication of MEMS devices with heightened mechanical performance and capabilities. Hence, different materials including metals, ceramics and photo-curable polymers have been used efficiently in MSL process [47,48].

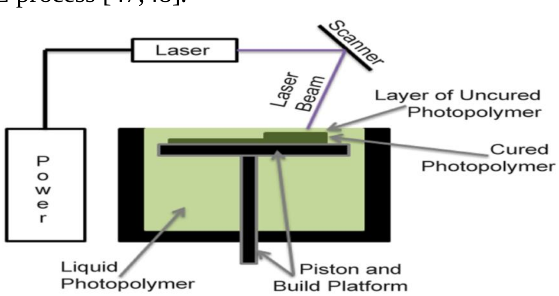
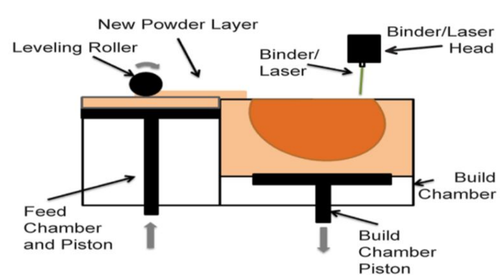


Fig. 2 The SL process [25]



Fig, 3 The SLS process [25]

B. Selective Laser Sintering (SLS)

It was developed at the University of Texas - Austin by Joseph Beaman and Carl Deckard in the mid 1980's [49]. In SLS, layers of fine powders that are fused together with a binder or laser beam, are sintered together using a high temperature layer. Once each layer is produced a fresh powder layer is spread by a roller on the bed repeatedly until the part is completed [50]. The excess powder which serves the function of a support material can be later released by vacuum and further detailing and processing like sintering, infiltration or coating can also be done. The driving factors to the efficacy of this process are packing and powder size distribution which also control the density of the printed devices and parts [51]. Also, the achievable resolution is governed by multiple factors including laser focussing, laser beam power as well as on the powder material size.

1) *Advantages of SLS Technique:* SLS can be applied to a wide variety of materials from: polymers such as polycarbonate (PC), polyvinylchloride (PVC), resin, nylon and polyester [52] to metal and ceramic powders [53,54]. Also, as no liquid binding material is essential for device production it is possible to produce complex micro components with fine resolution and enhanced printing quality. The above advantages prove this process to be beneficial for advanced applications in various industries such as aerospace, electronics and scaffolds for tissue engineering where different powders such as tungsten, Cu, Ag and stainless steel alloy 316L have been effectively produced and processed. Micro technologies of particular interests include micro moulded parts, endoscopes, minimal-invasive surgery, connectors and microsensors, micro implants, micro heat exchanger and microreactors.
2) *Drawbacks of SLS Technique:* However, the thermal heating caused by the laser and subsequent cooling results in the deformation or shrinkage of models made by SLS [55]. Thinner layers and powders with smaller particle sizes are essential for achieving finer details but such finer particles are generally more reactive to oxygen and humidity and hence the process should be performed in vacuum chamber to overcome the challenges of humidity and oxidation and prevent corrosion. Also, owing to the prevailing interparticle forces the fine powder layers are very loose [56] and hence special collection methods are essential to prevent agglomerates. Other challenges include high porosity when powder fuses with binder, high costs and slow speeds.
3) *New Developments in SLS:* A special roller-based powder deposition mechanism which included powder reservoir, a deposition carriage, a processing zone, rolls and electric motors was proposed by Haferkaup *et al*. [57]. The powder layer once generated is fed between the rolls having an opposite direction of rotation. Here, the roll separation distance is adjustable at the places where thickness of layer is variable [1].

In 2003, The Laser Institute Mittelsachsen proposed the MLS System [58,59,60,61] which was perceived as a promising approach for effective precision micro-tooling and complex microdevice fabrication. The system included a powder coating and two special rakes that are employed for carrying out circular sweeping of powder materials on the bed. Powder particle size and composition or blend of powder can be are easily controlled and can be utilized to good effect in the fabrication of different microparts produced from a wide range of metals. Non-metallic materials processing however still poses a significant challenge. The first successful developments towards non-metallic material fabrication occurred in 2005 while generating oxide ceramic bodies [62,63]. However, more development is required for new processing technology and parameters for effective laser sintering of ceramics [63]. Powder size in the sub-micrometre range is essential for achieving the desired resolution and the coefficient of absorption of the material for the wavelength of laser used should be sufficiently high for effective laser energy transfer into the material. The composition of glass and crystalline fraction should be high enough to allow for part generation having good sinter quality. At present MSL is facing challenges such as lesser choices for material selection, power handling (recoating), part cleaning/removal, low achievable resolution and high surface roughness, that is restricting its usage method in micro-industries. Even finding the process parameter for different material is a concern.

The problem of limited materials can be looked for with the replacement of conventional powder recoating methods with dry powder dispensing techniques which have shown great ability in precise placement of fine powders [64,65,66]. Also, inclusion of selective powder dispensing mechanism in MSL process is a promising approach improve the resolution and provide an efficient alternative to the problem of fine powder handling.

SLM Process is a rapid manufacturing (RM) technology, quite similar in principle to SLS process with an exception of the complete melting of powders for achieving superior mechanical properties and denser functional parts by a high energy density laser scanning process. Specialized SLM systems for microfabrication has not yet been developed. However, an available commercial system of SLM 50 has successfully processed a wide variety of materials including aluminium (AL), super alloys, stainless system, cobalt (Co), titanium (Ti) and chromium (Cr) [1].

C. Inkjet Printing Process

Lord Rayleigh first gave the concept of inkjet printing initially in 1878 [67] and this technique was later patented by Siemens to give the first two-dimensional (2D) inkjet type printer named as Rayleigh break up inkjet device which has been extensively used for ink printing on paper [68]. Later on, it was successfully utilized for producing printed structures made out of ceramics, sol-gel, nucleic acid, metals and conductive polymers. Inkjet printing process are based on inkjet technology and include layer by layer deposition of a liquid material in droplet form (also called ink or ink) and their stacking and arrangement. The process is a non-contact method that employs either electromagnetic, thermal, or piezoelectric technology for deposition of tiny droplets of ink or other materials onto a substrate as per the given digital instructions. The droplet deposition is carried out by heating or mechanical compression to facilitate ink drop ejection [69]. The material often solidifies after the deposition process either via cooling (e.g. by vitrification or crystallization) or solvent evaporation or through chemical changes (e.g. through the cross-linking of a polymer). The model is heated on completion of the deposition process to improve its binding powders at desired regions and the unbound powder particles function as support material during the process and are later removed after fabrication. The diagrammatic representation of the inkjet printing method is shown below in figure 4.

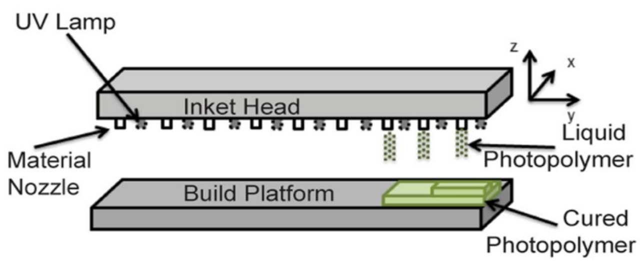


Fig. 4 The inkjet printing process [25]

This printing method has been most widely used for rapid prototyping of ceramics. An injection nozzle is used to pump and deposit a stable ceramic suspension like zirconium-oxide powder in water [70] in its droplet form onto the substrate. These droplets once deposited in a continuous pattern, solidify and possess sufficiently high strength to hold onto the subsequent layers of the deposited material. The highlights of this method are that it is efficient and fast, provides high flexibility in design and is capable to print complex designs.

The ceramic inks which are mainly used are liquid suspensions and wax based inks. Liquid suspensions get solidified using liquid evaporation process whereas wax based inks are first melted and solidified after deposition on a cold substrate in order to solidify. The quality of inkjet printed devices and parts depend on ink and solid content viscosity, printing speed, nozzle size and particle size distribution in case of ceramic printing [22]. The behaviour of drops and liquid jets are affected by surface tension, viscosity and inertia of the ink and solid content.

Two broad categories of procedures are performed for creating droplets, continuous inkjet (CIJ) and drop-on-demand (DOD) techniques. CIJ Technique was developed in the mid 1960's at the Stanford University and involves the use of a printer head supplied with electrostatic plates, to direct ink droplets onto paper for fabricating devices or into a waste compartment where they can be later recycled and reused [71]. The droplet spacing and size are determined by the applied pressure and wave pattern. Figure 5 shows the principle of operation of a continuous inkjet printing process.

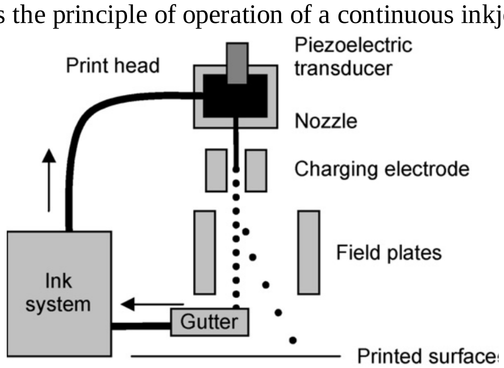


Fig. 5 Continuous inkjet system [72]

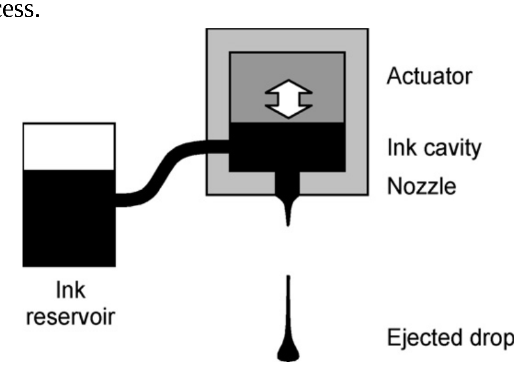


Fig. 6 Drop-on-demand Print head [72]

DOD technique was developed by Zoltan [73], Kryser and Sears [74]. In DOD technique droplet delivery is done only when demanded and hence the need for unused liquid recycling is omitted. In response to an activation signal, the ink vet releases droplets of desirable material, through an actuator generated pressure pulse. The principle of operation of DOD is shown in figure 6. Due to operating with fluids of higher viscosity at higher drop velocity DOD has more potential for 3D microfabrication as compared to CIJ systems [72]. The two kinds of actuator which are commonly used are thermally and piezo-electronically actuated DODs. Thermally actuated DOD where glancing and fast heating of the ink is achieved inside the ink reservoir using a small electrical heating element that creates a transitory bubble of vapour. This vapour bubble is responsible for injection of a jet of ink from the nozzle. The other process which is more common in industrial system is the piezo-electronic actuated DOD. In this, the internal volume changes of the ink reservoir are achieved using pressure waves set up by an electric field. These waves result in the ink injection from the print head nozzle and corresponding filling up of the printhead from the ink reservoir [72].

Inkjet printing is efficiently employed for microfabrication and microprinting of both non-metallic as well as metallic materials but DOD metal ink printing requires special conditions and configurations and parameter settings in order to control jetting process for formation of well defined droplets. For e.g. jetting processes can yield microdevices with higher mechanical properties, when performed in low-oxygen environment as oxidation of jets and microdroplets is avoided, otherwise the oxide layers may bring about a change in the physical properties of jet surface and may prevent jet disintegration [75,76]. Also, in the argon environment where oxygen concentration is not more than 10 ppm a uniform-sized alloy droplet stream is produced [77]. In order to have a successful metal ink DOD, the three essential conditions are: Stable jetting droplet generation, sufficient drying of droplet before the launch of the subsequent droplet and stable base structure initiating 3DP. These three requirements are strong functions of ink properties (surface tension and viscosity), jetting parameters (voltage magnitude, signal width and frequency) and environment (temperature, pressure and humidity).

1) *Advantages of Inkjet Printing:* There is no requirement of liquids with modified viscosities or photopolymerizable materials as inkjet printing is a powder-based rapid prototyping method. Glass materials or polymer ceramics can be combined with liquid binding materials to generate 3D models [78] further expanding the applicability of this technique in areas of art designing and industrial modelling [79] significantly.
2) *Disadvantages of Inkjet Printing:* However, the dominance of the physical and chemical properties of the printed liquid's over those of the printed device can prove to be a disadvantage. Another limitation of inkjet printing arises due to the incomplete interaction of powder particles with binder liquid. This poor interaction results in light scattering and hence reduced optical transparency and coarse resolution of finished devices which is a severe limitation in microscopic devices. The unbound particles can promote poor surface roughness and higher porosity in the finished materials which can be both limitation or an advantage depending upon the end application.
3) *Application of Inkjet Printing* The process has been extensively used in MEMS and MOEMS systems which involve 2/2.5 D production such as mask less printing of electronic circuits using electrostatic inkjet printing [80] and solder printing for IC test boards [81]. It has shown great ability to print a wide variety of microproducts including solders, optical polymers, light-emitting polymers, thermoplastics, micro-lenses and organic transistor. Tropmann *et al.* [82] proposed for a pneumatically actuated inkjet printing system having a star shaped nozzle to overcome the challenges faced in the of fabrication of good quality 3D metallic microstructures i.e. poor surface quality and porosity. The specially constructed nozzle uses capillary forces to stabilize the liquid plugs in its centre and hence allows for a stable jet of liquid metal microdroplets. It can be operated in both continuous droplet dispensing mode or drop on demand (DOD) mode.

D. Three- Dimensional Printing Process

The 3DP process developed in the Massachusetts Institute of Technology [83] is quite similar in principle to inkjet printing technology. This method involves the deposition of binder material over the powder bed surface and ensuring the sticking of powder particles. In the next step the powder bed is lowered via a piston to allow for the spreading of a fresh powder layer over the previous layer, followed by the binder deposition over the new surface. The above procedure is repeated to build the whole part [84]. With regard to 3DP method, larger particles have lower surface per volume and are simpler for spreading [85]. Also, larger pores present in the layer particles provide more freedom for the binder particles to migrate in the power bed allowing for fabrication of homogenous devices and parts [86]. Powders with smaller sizes and thinner layers are essential for achieving finer details which is very similar to micro-sintering process. The benefits of these finer powders are generation of thinner layers, promoted printability and lower surface roughness [87]. The quality of parts and devices printed by 3DP are determined by deposition speed, shape and size of powder particles, processing techniques and rheology and chemistry of the binder [88,51].

1) *Advantages of 3DP:* This process has the capability of producing devices made from a wide range of materials including metals, polymers with unique array of geometries, ceramics and shape-memory alloys (SMA) [89,90,91,92]. One great positive of this method is that it allows for fabrication and design of complicated shapes involving a novel macro and microarchitecture and a fully interconnected pore network [93]. Direct fabrication of micro-ceramic moulds can also be achieved using 3DP process. There also lies a great opportunity to produce complex final microproducts by combining inkjet printing process and 3DP process. Inkjet printing process of tailor-made inks on the already developed surfaces using the 3DP process is a new dimension of this technique where new opportunities can be explored. Other micro-deposition process such as aerosol jet process also support writing in 3D space.
2) *Disadvantages of 3DP:* However, the process has high porosity, as a result the printed parts are of lower density as compared to laser sintering or melting [51]. Other main challenges include poor resolution of the parts developed by this process and difficulties faced in powder recoating and part depowdering on a micron scale. But 3DP process like other powder-based processes have very limited potential for correcting these defects since decreasing the powder particle size makes the recoating process even more difficult and challenging [1].
3) *Newer Variations in 3DP:* Digital Metal Technology is a precision inkjet technology which has the capability to produce highly complicated shapes and intricate features and designs for micron size metallic parts, cost effectively in low to medium volumes. The operation of this process involves the combination of 3DP method and sintering process as post processing techniques for production of micro-components having higher accuracy and precision. Moreover, a special sintering aid is spread as a binder over the powder in the regions of the part cross-section, to allow for quicker fusion of the area in a sintering furnace. The use of sintering aid as a binder allows the product to sinter in less time and at lower temperatures in the furnace as compared to encompassing powder, which is not used.

In the other variant, micro 3DP technology, the thermal printing heads (as used in conventional 3DP) are replaced by high-resolution piezo-electronic heads for fabrication of 3D microparts. The quickness of this process as compared to the other micro-additive manufacturing processes makes the process most suitable for micro-prototyping and direct mass production of microparts [94, 95].

E. Fused Deposition Modelling and Extrusion-Based Techniques

FDM is a special technique of additive manufacturing processes based on extrusion. Such techniques employ a computer-controlled deposition nozzle that deposits material in a continuous flow to produce 3D objects and patterns with desired architecture and composition. The extrusion technique can be classified into two categories – processes that involve melting of material and processes that do not involve melting of material. Extrusion techniques in which the material gets melted includes, FDM and its variations like precision extrusion deposition (PED) [96], multiphase jet solidification (MJS) [97], 3D fibre deposition [98] and precise extrusion manufacturing (PEM) [99]. Whereas, solvent-based extrusion free-forming [100], 3D bio-plotting [101], Pressure-assisted micro syringe (PAH) [102], robocasting [103], low-temperature deposition manufacturing [104] and direct-write assembly [105] are processes that do not involve melting of the material. The non-heating processes basically have used four major nozzle designs namely piezoelectric actuated, pressure actuated, solenoid actuated and volume driven injection nozzles. Whereas for processes involving heating of material mini-screw extruder and wheels driven by filament are the two nozzle types generally used. There are some limitations faced in extrusion-based processes with respect to the melting of the material in the region of microfabrication. The preferable range of width of the rod is 20-30 μm and that of flow volume is in the order of nano-litres per second for accurate microfabrication. Further the system must also be supplied with control systems and accurate flow delivery to optimize the accuracy of the technique. Introduced by Scott Crump of Stratasys, FDM is an extensively used AM technology for the application of rapid prototyping. In this technique 3D device fabrication is achieved by extrusion of thermoplastic filaments and deposition of the materials in a semi-liquid state on the platform layer wise [106,78, 107]. The process involves movement of the material and the thermoplastic filaments which are used to build the material to tip of the extruder nozzle. Which are then with the use of temperature-controlled units heated in order to become semi liquid. Following this the pattern of each cross-sectional layer is traced by the head of the nozzle and subsequently the semi liquid material is ejected by it. The platform lowers and the successive layers are deposited in the similar fashion yielding the desired complex part. The thermoplastic property of the filament is utilised for fusing of filaments while printing and their solidification at room temperature after printing. In order to ensure that the 3D FDM printed parts have the same durability, mechanical properties and stability, the thermoplastics chosen for the manufacturing of the printed devices is same as the ones employed in injection machining [108].

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The main parameters which determine the mechanical capabilities of the printed devices are air cavities, filament orientation, width and layer thickness [109]. Figure 7 illustrates the FDM process.

1) *Advantages of FDM:* The FDM process allows the user to have more control over part production and experimental use as the process is capable of creating objects from multiple material types by printing and a subsequent change in print material. FMD can not only fabricate parts from conventional materials such as polystyrene, ABS and PC but also from bioresorbable materials [110], metals [111,112], glass reinforced polymers [113] and ceramics [111,114]. High speed simplicity and low cost are the main benefits of FDM.
2) *Limitations of FDM:* The main challenges to the FDM process include poor surface quality [115], limited number of thermoplastic materials, layer by layer appearance of the final part and weak mechanical properties [109]. Surface defects such as chordal and staircase defects are also witnessed when using FDM. The material extruded from the nozzle of the extruder depends on the diameter of the filament fed and the density. Internal defects are commonly observed the two parameters are imbalanced [116,117].
3) *Development of New Configurations without Material Melting:* To improve upon the on the limitations of FDM related to shape and resolution of the feedstock, various modified versions of FDM have been developed such as PEM, PED, MJS and 3D Fibre deposition. However, the adverse effect of high temperatures used in the process on the raw material and the resolution still persists in these modifications of FDM. As a consequence, further research was carried out in order to develop new techniques that do not involve heat to melt the material. With the focus on the preservation of the bioactivities of scaffold materials in the biomedical industry [1].

PAM (Pressure-Assisted Micro syringe) is one such technique. The technique involves deposition of the biomaterial on the substrate using a micro syringe operated by pneumatic control [102]. It can be used for effectively printing scaffolds using polymers such as gelatine, PCL, alginate hydrogels scaffolds, PLGA and PLLA (poly l-lactic acid) [118,119,120,121,122]. The other technique is 3D bioplotting which was initially developed for achieving the simplification of hydrogel manufacturing and for production of micron sized rods for research work in the soft tissue engineering. In the process, the extrusion head shows 3D motion whereas the stage is kept fixed. Viscous material is plotted into a similar density liquid plotting column using a stepper motor (injection nozzle driven by volume) or a filtered air pressure (pneumatic nozzle) [1]. The method permits both continuous filaments dispensing and discontinuous dispensing in the form of micro-dots. Bioplotting can be effectively used to print parts made up of a large range of biomaterials such as thermostat resins, polymer bells, agar and gelatine polymer solutions [123], as well as natural polymers including collagen, PLGA, PLA and PCL. Owing to the advantage of no heat input, bioplotting can be utilized for biocomponents and cells that are thermally sensitive. Another technique, Robocasting is an extrusion-based AM technique specifically developed for processing of ceramics. In this technique colloidal ceramic slurries which are highly concentrated (50-65% volume of ceramic powder) are deposited using computerized control [1]. In solvent based extrusion free-forming technique, the material is continuously deposited with the help of a nozzle in the form of paste or particulate slurries. The process is basic with change of phase based on solid evaporation. This technique has been specially developed for the production of bioceramic scaffolds [124,125,126,127] and electromagnetic band gap materials [128]. Ceramics, polymers and a suitable solvent are mixed together to form a paste with specific ratios yielding high strength. Ensuring appropriate content of polymers, various defects such as surface fracture, drying cracks and dilatory can be overcome in water-based extrusion systems [1]. In the direct-write assembly, variety of inks can be utilised to be deposited in a pattern that can be in both planar or 3D shape involving very fine feature sizes. The process involves ejection of the ink from an individual nozzle by using compressed air. It has been used to process variety of inks including nano-particle filled inks, polyelectrolyte inks, colloidal suspensions, polymer melts, sol-gel and hydrogels. Polyelectrolyte ink writing has to be carried out in a reservoir-induced coagulation. On the other hand, sol-inks have the advantage of ensuring a controlled process of deposition and printing directly in air [1].

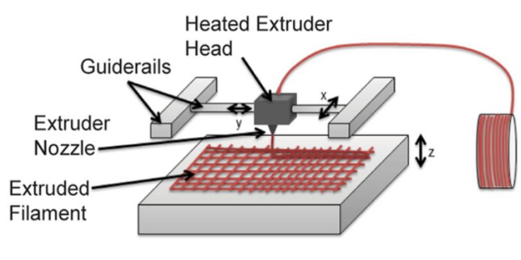

Fig. 7 The FDM process [25

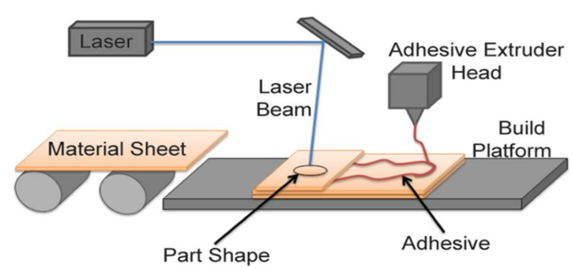

Fig. 8 The LOM process [25]

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TABLE 1
SUMMARY OF SCALABLE AM METHODS [21]

Methods	Materials	Application	Benefits	Drawbacks
Fused deposition modelling	Continues filaments of thermoplastic polymers Continues fibre-reinforcement polymers	Rapid prototyping Toys Advanced composite parts	Low cost High speed Simplicity	Weak mechanical properties Limited materials (only thermoplastics) Layer-by-layer finish
Powder bed fusion (SLS, SLM, 3DP)	Compacted fine powders Metal, alloys and limited polymers (SLS, SLM) Ceramic and polymers (3DP)	Biomedical Electronics Aerospace Lightweight structures (lattices) Heat exchangers	Fine resolution High quality	Slow printing Expensive High porosity in the binder method (3DP)
Inkjet printing and contour crafting	A concentrated dispersion of particles un a liquid (ink or paste) Ceramic, concrete and soil	Biomedical Large structures Buildings	Ability to print large structures Quick printing	Maintaining workability Coarse resolution Lack of adhesion between layers Layer-by-layer finish
Stereolithograph y	A resin with photo-active monomers	Medical prototyping	Fine resolution High quality	Very limited materials Slow printing Expensive
Laminated object manufacturing	Polymer composites Ceramics Paper Metal-filled tapes Metal rolls	Paper manufacturing Foundry industries Electronics Smart structures	Reduced tooling and manufacturing time A vast range of materials Low cost Excellent for manufacturing of larger structures	Inferior surface quality and dimensional accuracy Limitation in manufacturing of complex shapes

F. Laminated Object Manufacturing (LOM)

LOM was developed by Helisys [129] and is one of the first commercially available AM method. Here, generation of 3D model is achieved by stacking layers of defined materials in the form of sheets like metal, plastic and paper [52]. The process involves the cutting of expected profiles from an uninterrupted roll using a laser beam, to create the final part layers. Once the stage is loaded with first layer of sheet material, a razor or a laser (CO_2 lasers, as utilized previously [130]) are used to cut and trace the defined cross section in order to create the pre-defined pattern [131]. After getting rid of the excess material of the previous layer, the following layer covers the previous layer and the next pattern is created using laser tracing. The excess materials can be later recycled and reused [46]. To stick the layers together, plastic post heat activation is applied on one of the surfaces of the final part and the paper. The adjacent layers can also be combined by welding e.g. for paper and metal. LOM can be used with a wide range of materials like composites, ceramics, paper, polymer and metal filled tapes. A broad range of materials such as paper, metal filled tapes, ceramics, polymers and composites can be used for LOM. The nature of the material and the required properties in the final part further control the need of post-processing treatments like high temperature treatment [21]. The detailed process is depicted in figure 8.

1) *Advantages of LOM:* In the process heating is required either on the roller or on the support stage to ensure that adhesive bonds the sheet together tightly. This heating process has a quite low effect on the non-uniformities that finally appear on the final fabricated part especially in comparison to different types of defects prevalent in other techniques such as FDM. LOM is utilised in numerous industries like electronics and smart structures, paper manufacturing, and foundry industries. Devices involving a number of processors and sensors are classified as smart structures [21]. For fabrication of ceramic parts possessing small cavities in the interior of the part and channels suitable for microfluidic devices, LOM is extensively used [1].
2) *Drawbacks of LOM*: Control over the local temperature is an important factor affecting the process. Excessive heating of the adhesive can damage it causing structural damage. On the other hand, insufficient heating of the adhesive can cause the part to become delaminated [132]. As the process is cost and time effective it is widely employed for fabrication of large structures. However, the process has lower dimensional accuracy and inferior surface quality (without processing) in comparison to other methods. Also, the removal of excess parts after the component is formed is time-consuming in comparison to other power-bed methods, and hence this method is not recommended for complex shapes. Another drawback of the process is that only materials which can be drawn into sheets and can form a bond with the adhesive can be used.
3) *New Subclasses of LOM:* New variations of LOM have been developed to overcome some of its limitations. One of them being a combination of ultrasonic metal seam welding and CNC milling known as Ultrasonic Additive Manufacturing (UAM) [133]. Of all the AM manufacturing methods this technique is most favourable for metal surfaces construction at low temperatures [134,135]. Another highlight of this process is that it allows for construction and specification of cavities in the devices specifically designed for sensors, pipes, electronic devices and other features. Through the application of direct write technologies in the lamination process of UAM many electronic devices can be generated.

CAH-LEM Process (computer aided manufacturing of laminated engineering materials) is a special micro-LOM process, which are based on the slices produced by laser cutting of green ceramic or metal tape which are then later stacked to produce the part. In the next step layers are fused together by the application of pressure and heat and afterwards the green model is then furnace treated to impart sufficient strength. The process offers the capability to process five materials having different thickness, with one or more of the selected materials functioning as support members which provide for building of internal microchannels and overhangs. These materials are then removed using chemical/thermal methods. The main drawback of this technique is the dimensional inaccuracies arising from the large shrinkage levels (12-18%) due to thermal processing [46]. CAM-LEM process allows for the production of high performance micro-fluidic devices made from metal or ceramic. These provide high temperature resistance, better strength and chemical resistance than silicon or plastic and better strength than glass. It can be used for the production of miniature diagnostic devices, microsensors, micro-reactors and micro-fuel cell components and heat exchangers.

III. 3D DIRECT WRITING PROCESS

DW processes were initially developed with an aim to perform two dimensional(2D) Writing but certain methods including; Laser Chemical Vapour Deposition (LCVD), Focussed Ion Beam (FIB) DW, Laser Induced Forward Transfer (LIFT), Matrix Assisted Pulse Direct Write (MAPLE), nozzle dispensing processes (including precision pump and syringe based deposition techniques) and aerosol jet process can be utilized to produce high resolution 3D devices. Out of these 3D-LCVD and FIBDW are used more readily and efficiently in the production 3D microdevices, whereas nozzle Dispensing techniques are currently utilised in the production of 3D micro-periodic structures. DW approaches including aerosol jet process, MAPLE and LIFT are in sparse and require more thrust for their development for production in true 3D microstructures. Certain nozzle dispensing processes including PAM, direct write assembly etc. have already been discussed in section 2.5.4 along with FDM process in some detail. The following section contains a brief description of two most utilised DW techniques namely LCVD and FIBDW.

A. *Laser Chemical Vapor Deposition (LCVD)*

The production of vapor deposited films has now become a mature technology and are utilized in wide variety of applications. Each of such processes has its own unique characteristics that make it the best suited for that particular application. For example, chemical vapor deposition (CVD) when conducted in plasma i.e. plasma enhanced CVD is employed when temperature levels of the substrate have to be restricted in a range which cannot be achieved with conventional CVD. Use of metalorganic reagents (MO-CVD) also allows for the deposition at lower temperatures but its application is restricted due to the high reagent costs. Laser CVD is a process where the substrate is heated at a spot using the heat from the laser beam. The process is utilized where patterning, writing or growth of 3D structures is desired.

The physical vapor deposition (PVD) variants like evaporation and sputtering permit the use of even lower temperatures of substrate than CVD. Accordingly, such coatings are having a low degree of crystallinity than CVD and are more stressed [136]. Evaporation, sputtering, and Laser CVD are essentially line of sight processes. A thorough coating of the substrate surface can be more effectively done by other CVD processes. Chemical vapor infiltration which is a variant of conventional CVD can be used to deposit inside a preformed fibrous matrix of a fibre reinforced composite [137].

A laser beam is employed for inducing chemical reactions between reactants to generate solid deposits on the substrate surface in laser CVD process [138,139]. LCVD reactions are generally classified as either decomposition reactions, which involves decomposition of a single reactive gas, or combination reactions, in which components of two or more separate gases combine. Decomposition reactions usually involve the dissociation of metal halide components in the presence of excess hydrogen [136].

In LCVD process, focussing of the laser beam using an optical microscope lens to a spot is critical. The focussed beam produces gaseous reactants of the materials whose deposition is desired and then these reactants are fed into a build chamber. Laser beam scanning is carried out for heating the substrate to bring about effective selective dissociation of the reactant gas, resulting in formation of thin layer deposits of material on the substrate. Hence by repeating laser scan, desired micro component can be made in a layer-by-layer manner.

Multi-material structures can be formed by feeding multiple gases into the reactant chamber at different times. Similarly, gradient structures can be produced by varying the concentration of the gases within the mixture [1]. At times a localized gaseous atmosphere can be created with flowing jets of gas instead of feeding the precursor gas in the reactant chamber. Such a system has been developed at the Georgia Institute of Technology. The system includes a small chamber which contains the reactant gas (which is usually exceedingly corrosive and/or biologically harmful) that is kept in isolation from the system mechanisms and motion controllers. The small reaction chamber allows for multi-material deposition by its ability to quickly change the reactant gas materials. Other benefits include, higher corrosion resistance of the hardware and better monitoring of the dimensional and the thermal characteristics of the deposit which results in effective controlling of the process parameters to produce deposits having desired geometries and properties [46].

Depending upon the initiation mechanism of chemical reactions, LCVD processes have been categorized as photolytic or pyrolytic. With an exception of a few deposition systems most LCVD techniques predominantly rely on one class of reactions [22,141,142].

1) *Photolytic LCVD Process:* Photolytic LCVD uses energy of photons emitted from a laser beam to bring about bond cleavage within reactive gases. A solid deposit on the substrate surface is formed after the gaseous molecules further decompose or recombine and thinner layer deposits can be achieved when the laser beam is made parallel to the substrate. The most commonly utilized lasers in this process are the pulsed lasers (Ar+, ArF, KrF) in the UV spectrum. The layer and the reactive gas 'tuning' i.e. absorption of the laser beam wavelength by the reactive gases is essential for effective deposits. This 'tuning' restricts the flexibility of photolytic LCVD technique. The absence of high temperatures serves as an advantage as substrate damage and thermal stresses build up between the layers is minimized [136]. Several kinetic [143,144], fluid flow [145] and process [146] models have been developed for the photolytic process. Empirical observations indicate that the deposition rate and material properties are affected the most by the parameters like laser power and total pressure [147].Photolytic depositions have been used to fabricate mirrors [148] and lenses [149] and have been used for producing thin surface coatings for corrosion resistance [150] and solid lubrication [151]. Patterned depositions have also been considered for X-Ray Mask Repair [152] and Electronic Circuit Repair [153].
2) *Pyrolytic LCVD Process:* It is a thermal process in which chemical deposition occurs on the substrate surface after it is heated to a high enough temperature using the energy from a laser beam. Due to restricted heated zone formed by a focused laser spot, parts with very fine resolution can be produced. The heated zone is defined by the laser beam diameter and the optical and thermal properties of the substrate. Continuous wave infrared lasers (e.g. CO_2, Nd:YAG) have been predominantly employed for pyrolytic process, although recently argon ion lasers have also been developed. The high spatial resolution offered by pyrolytic methods make it the ideal manufacturing method for fabrication of small parts and complex designs [154,155]. The pyrolytic LCVD technique is based on the traditional CVD process, in which coatings are deposited uniformly at the surface of small and large substrates using thermally activated chemical reactions. Moreover, the range of deposited materials does not depend on the laser beam wavelength selected. Materials such as tungsten, tungsten carbide, titanium nitride, titanium carbide, silicon, silicon nitride, silicon carbide, carbon, boron, gold and aluminum have been deposited using the pyrolytic LCVD techniques [136].
3) *Advantages of LCVD Process:* The single material deposition technique employed in LCVD, imparts superior mechanical properties and higher thermal stability resulting in the deposited material being impurity free, possessing higher degrees of

crystallinity and lower porosity levels. Alternative deposition techniques such as sputtering or evaporation and plating are not desirable as the produced materials contain unwanted residual stresses. LCVD allows for deposition of dispersed phase component materials possessing improved mechanical properties. Preparation of laminated or graded structures with improved properties is a specific application of this process. Variation in the reagent gas mixture present near the reaction zone can be carried out for deposition of different materials. Higher flexibility in material selection and spatial resolution offered coupled with improved structural integrity are other positives of this method which allow for production of parts involving improved performance and higher service life.

4) *Disadvantages of LCVD Process:* LCVD has low deposition speeds and suffers from high system complexity as compared to other DW methods with an exception of ink-based technology. Deposition at higher temperatures and higher production costs are the other drawbacks of this process. The deposition capability on large pre-existing structures is limited by the special controlled atmosphere needed for the deposition process [46].
5) *Applications of LCVD:* Ceramic and metal based microparts can be generated from LCVD techniques with different material specific precursor or reactant gases employed. Furthermore, it can be used to build multi-layered carbon structures and carbon fibres [46]. This method is capable of depositing various materials including silicon carbide, molybdenum, carbon, boron and boron nitride onto various substrates such as alumina, silicon, tungsten, zirconia and graphite, depending upon the application [1]. It is best suited for high precision customized production of low volume speciality parts like fibres, coatings on thermally conductive materials, diamond like carbon (DLC), micros-solenoids, antennae and optical devices and structures [136]. The enormous variety offered in deposit geometries and materials serve as an appropriate motivation for write developments in this technique. The LCVD resolution is a function of substrate thermal properties, laser energy density and wavelength (which control the heated zone size) and laser beam diameter [46]. The deposition rates depend on the process parameters such as gas pressure, powder density and scanning speed. Increasing the laser power intensity and precursor gas pressure can speed up the deposition process [1]. Also there exists an inverse relationship between deposition rate and scanning speed [156]. A wide variety of metals, ceramics and composites can be deposited depending upon the gases present at the reactive zone.
6) *Latest Advancements in LCVD*: LCVD has been explored to produce three-dimensional shapes and multilayered materials. The versatility of LCVD process is demonstrated by the spheres, helical structures, blocks and complex fibrous scaffolds fabricated by this technique. In Selective Area Laser Deposition Vapor Infiltration (SALDVI), more rapid fabrication of structures can be achieved by integrating layer-wise deposition of powders in LCVD process than when employing traditional LCVD technique alone. The powdered materials are bounded together in the laser heated regions of the powder bed with the solid material created from the vapor phase serving as the binding agent. However, the parts generated from SALDVI may suffer from porosity and are composite in nature [46].

B. Focussed Ion Beam Direct Writing (FIBDW)

In principle FIBDW is quite similar to LCVD process except for the fact that here a focussed ion beam is employed for the deposition process instead of a laser beam.

The FIB is generated from a liquid gallium source that is placed in contact with a tungsten needle resulting in the heating of the metal to wet the needle and produce a strong electric field which ionizes the gallium metal to emit ions. Electrostatic lenses are used for accelerating and focusing of the emitted ions in a small stream [46].

In the presence of gaseous precursors, the build substrate is scanned by the beam, resulting in deposition of solid material onto the substrate [157,158].

The ion beam is operated in a beam energy in the range of 10 and 50 keV, with beam currents varying in the range 1pA and 10nA. When high energy ions strike a surface, four mechanisms can take place: electron emission, sputtering of neutral and ionized substrate atoms, emission of photons and displacement of atoms in the solid [72].

The sputtering and atom removal caused by the collisions of high energy gallium ions can be detrimental to the part quality so FIB processing should not be done alone. If the surface change in the machining zone caused by the deposition of the removed material and ion implantation can be properly and effectively controlled, the implantation and to sputtering effects of gallium atoms, can prove to be of advantage.

As discussed above, there is a requirement of a precursor gas to be sprayed on the surface. For deposition of W, the organometallic gas is $W(CO)_6$ [159]. Other precursor gases are available for the deposition of conductors such as Cu, Pt, Mo, Al and Au and insulators such as TEOS, THCTS/O_2 and PMCPS/O_2[160,161,162].

1) *Advantages and Applications of FIBDW:* FIBDW has been effectively used for production of 3D devices and circuits from exclusive combinations of dielectric and metallic materials. Faulty IC circuitry is being repaired using both deposition and machining features of FIB. To avoid short circuitry the excess material removal becomes critical [36]. Conductive traces can be drawn using FIBDW in case of incorrectly formed electrical circuits/contacts. The method displays the capability of conformal deposition and forming 3D microstructures which further can be used for hermetic encapsulations for micro- sensors [73].
2) *Disadvantages of FIBDW:* FIB has restricted applications due to longer build times required for fabrication and is hence limited to low volume production, especially small-scale repair work [163]. The Ga^+ ions and organic contaminants present in the organo-metallic compounds which are employed in the metal deposition process affect the purity of FIB produced devices. Further, the resistivity of the FIB deposits is one or two orders of magnitude greater than those of pure metal owing to the large carbon contents [164].

IV. HYBRID PROCESS

It Includes EFAB and Shape Deposition Modelling (SDM)of 3D micro-additive technologies. The EFAB process utilizes electrochemical deposition and subtractive planarization in a layer by layer fashion to produce 3D devices whereas SDM uses additive and subtractive processes to produce 3D microstructures. However, only EFAB has displayed the ability for true 3-D micromanufacturing.

A. Electrochemical Fabrication Process (EFAB

It was invented at the University of Southern California in 1966, was then conceived as a “clean paper” alternative to microelectromechanical systems (MEMS) fabrication processes utilized to create far more complex 3D geometries as it allowed for easier designing at reduced capital costs while at same time providing an unprecedented amount of versatility [17].Initially the selective electrodeposition technique used in EFAB was called “Instant Masking”, that utilized pre-fabricated masks which removed the time-consuming and complex steps required in photolithography.

Thus, the procedure allowed selective deposition and other different EFAB processes which are carried out within a single, automated machine [165].

Devices made with EFAB are produced at a wafer scale using a solid freeform fabrication process that involves a combination of additive and subtractive processes. The process involves three steps: selective electrodeposition of one metal, blanket electrodeposition of a second metal and planarization. Here the metal deposition is achieved through electroplating and correspondingly yielding fully dense materials possessing excellent mechanical properties and a heightened biocompatibility for many applications.

The EFAB process is initiated with a blank substrate and involves development of devices in a layer-by-layer deposition manner and planarization of two or more metals. One metal which is structural is responsible for generating the desired features of the finished part or device, the other metal is generally sacrificial and serves the function of providing support during the layering process which is later on removed.

The first step involves selective electrodeposition of the first metal onto the substrate in some specific regions as defined by photomask corresponding to first cross section parts in a device. Generation of negative micro-moulds is also possible by custom-lithography process which involves exposure of UV light to a certain specific thickness of photoresist through the photomask [1]. In the second step, the chemical removal of photoresist is done followed up with the deposition of structural material in the hollow region formed by the photoresist removal.

The structural material serves the function of filling the gaps existing between parts on each layer as well. The two metals involved above are then planarized in third step using a proprietary process resulting in the formation of two material layers of precisely controlled thickness, flatness and surface finish.

The three steps are carried out repeatedly until all layers of the desired device are fully generated. In the last step, the device is rendered fit for end use application by the removal of the sacrificial material by a selective-etching process. If the first layer is made up entirely of sacrificial metal, then devices will be completely released from the substrate, which is particularly useful for medical devices [17,18].

The complete EFAB process is illustrated in detail in figure 9. EFAB is typically a net shape process with production of almost no burrs and only a small amount of distortion due to residual stress as the key highlights. Bulk ultimate tensile stress is credited with the formation of a majority of the portion of adhesion between the layers in a device formed by the EFAB process. Thus, for many devices generated by EFAB it can be said that they are nearly monolithic even though they are formed from discrete layers.

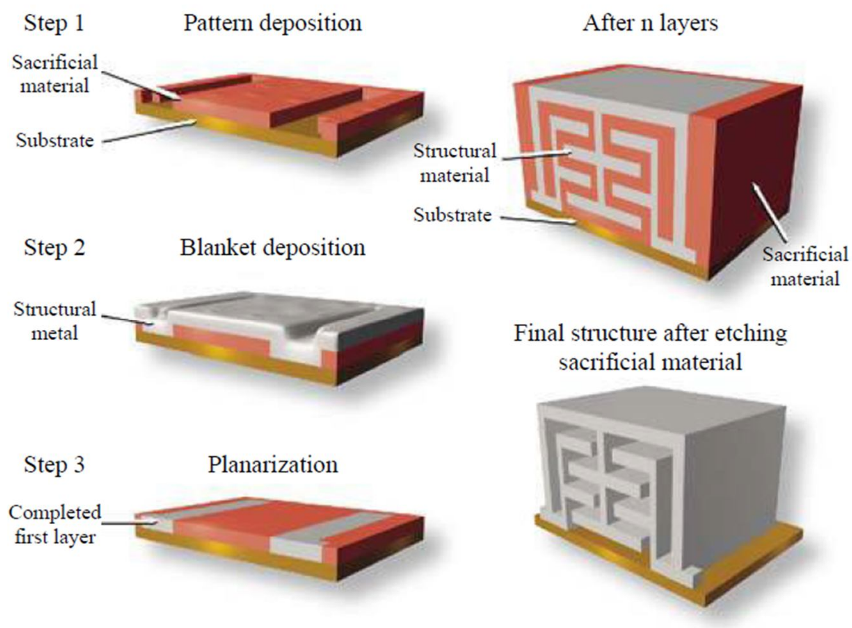

Fig. 9 The EFAB process [17]

Three types of materials, owing to their high levels of functionality are supported by the EFAB process for wide range of applications and are now fully commercialized. The first category is primary EFAB structural material which include valloy-120 which is biocompatible and possesses mechanical properties similar to medical grade stainless steel and palladium which again is an electroplated fine-grain metal and offers strength and hardness similar to that of cold-worked 316 stainless steel. Other features of palladium are: it is corrosion resistant, nonmagnetic, MRI-compatible and highly radiopaque. Both these materials achieve their mechanical properties as- deposited with no heat treatment needed. Secondary EFAB structural materials include edura-180 is an electroplated fine- grain rhodium formulation which is specifically used to improve hardness and provide good electrical conductivity and wear resistance. Its hardness exceeds the -57 Rockwell C hardness of hardened 440C stainless steel [17]. Depending on the end application requirements other materials can also be used EFAB process

1) *Advantages of EFAB:* EFAB process enables flexible, cost effective, highly repeatable production of metal devices measuring from millimetres to centimetres in overall size with their features measured in microns. EFAB processing is repeatable, accurate and free of many distortions. Device complexity can be extraordinarily enhanced at the millimetre to the sub-millimetre scale and allows for the effective development and fabrication of fully assembled mechanisms having moving parts independent of one another without any essential requirement of a micro assembly. It is a versatile, freeform process utilized for the production of metal structures and new devices at a small scale which were previously impossible to generate with an added benefit of reduced costs of production of existing devices. Features such as threads, micro textures, part members and logos can be added to devices at virtually no extra costs. It is possible to fabricate devices with undercuts, internal features, narrow and deep holes and slots, tall but thin walls, curved and non-circular holes and channels and sharp corners. Unlike, many manufacturing processes, the cost of EFAB is not heavily influenced by complexity. The primary cost driver for EFAB built devices is overall device size and number of layers required to produce it. EFAB technology in general is highly repeatable, owing to the usage of photolithography process for defining layer geometry. Moreover, bypassing the need for assembly can significantly boost quality. The process eliminates assembly processes relying on welding, adhesive fasteners which may cause device disintegration. Obviating, the need of assembly also results in lower risk of process glitches like the usage of wrong part, a part being forgotten or parts being assembled in the wrong order. Most EFAB built devices are produced monolithically from a single material [17]. The process has found application in micro industries concerning probes for semiconductor, memory chip and microprocessor testing, microfluidic devices, micro- and mesoscopic mechanical machine parts such as hinges, springs, screws, minimally invasive medical instruments and implants, , inertial sensing devices, optical scanners, motion sensors, compressors, pumps, solenoids, military fusing relying on watch-like mechanisms and millimetre wave components [17,165].

2) *Disadvantages of EFAB:* The most significant geometrical limitation of EFAB technology is related to the release of sacrificial metal. It is not possible to produce say a completely closed, hollow box as the requirement of the final product doesn't allow for the creation of a release hole and hence there would be no way to etch the sacrificial metal inside. In general, devices made with EFAB may require the creation of release holes can ensure proper and complete release of sacrificial material with only proper hole design complete release of sacrificial metal can be assured. In EFAB fabrication of devices with two or three dozen layers are common, with some devices built from up to fifty layers have also been made to this date.The layer count is greater by some magnitude as compared to microfabrication processes, such as surface machining which is commonly employed in the production of small-scale devices such as MEMS. The limiting factor on the layer count in EFAB processed devices is higher costs and longer processing time. The layered nature of the process is responsible for the formation of stair steps on some part surfaces and gives rise to inter-layer misalignment. Also, not all devices can be made fully preassembled using EFAB due to certain issues with stairsteps formation or limitations on minimum clearance between moving components. Layer thickness optimization can be used as an effective tool to minimize any objectionable surface roughness associated with stair steps. Other limitation in this process, is that devices produced cannot be too large. Also, at present range of materials is quite limited which do not meet all the requirements.

V. CONCLUSIONS

The highlights of 3D Printing include rapid prototyping, freedom of design and minimal waste generation. A comprehensive review of techniques, material used and their scope was carried out. Post processing techniques were analysed and challenges were looked into.

Each additive manufacturing method described up till now has its own advantages and limitations in production and fabrication of high definition prototype models.

Solvent capabilities for materials employed in 3D Printing is still under investigation but well documented literature on the reactivity of polymers and other discussed materials, with organic and aqueous solvents is available. In the AM methods involving laser operation, resolution apart from the laser spot size is also governed by the physical properties of the materials that affect and characterize the polymerization (SLA) or the thermal heating or cooling (SLA and LOM).

Resolution in techniques not involving laser action is limited by viscosity and cooling properties of material (FDM) and nozzle diameter. SLA and inkjet technology favour sample fabrication due to the fine microscopic feature sizes achieved and imparted in these technologies.

Due to the lesser time required for production and fabrication of unique parts and more provisions for increasing the speed and rate of production, scalable additive manufacturing is emerging as a viable alternative for traditional methods. The amount of time taken to manufacture a unique part is much less than that of traditional methods and it is significantly easier to speed up the process. The ability to produce products from a wide range of unconventional materials is also an added benefit of these procedures.

Laser CVD process produces solid deposits on a suitable substrate by chemical reactions which consist of gaseous reactants, which are initiated via a laser beam.

LCVD processes are categorized into photolytic where energy emitted from a laser beam is utilized for bond cleavage or pyrolytic in which laser beam energy is used to heat the substrate surface to a high enough temperature to result in chemical deposition. LCVD manufactured goods possess high purity and spatial resolution along with improved mechanical properties such as lower porosity, higher degree of crystallinity and enhanced flexibility. The major disadvantages for LCVD are lower deposition rates and chemical deposition at high temperatures.

SALDVI developed as a hybrid version of LCVD, is a combined layer wise deposition of powders for more rapid fabrication. FIBDW is similar to LCVD process except for the usage of focused ion beam instead of laser beam. It is a relatively slower process and has applications that are restricted to low volume production.

EFAB process is initiated on a blank substrate and involves development of devices by, layer by layer deposition and polymerization where one metal forms the microscopic features of finished devices whereas, the other material provides support and is sacrificial. It is flexible, cost effective, highly repeatable, accurate and free of distortions and features such as threads, microtextures can be added to devices at no extra costs. However, a significant geometrical limitation is the release of sacrificial material, so devices made with EFAB require the creation of release holes to ensure proper and complete release of sacrificial material. Also, the devices produced cannot be too large and suffer from "stair casing” effects.

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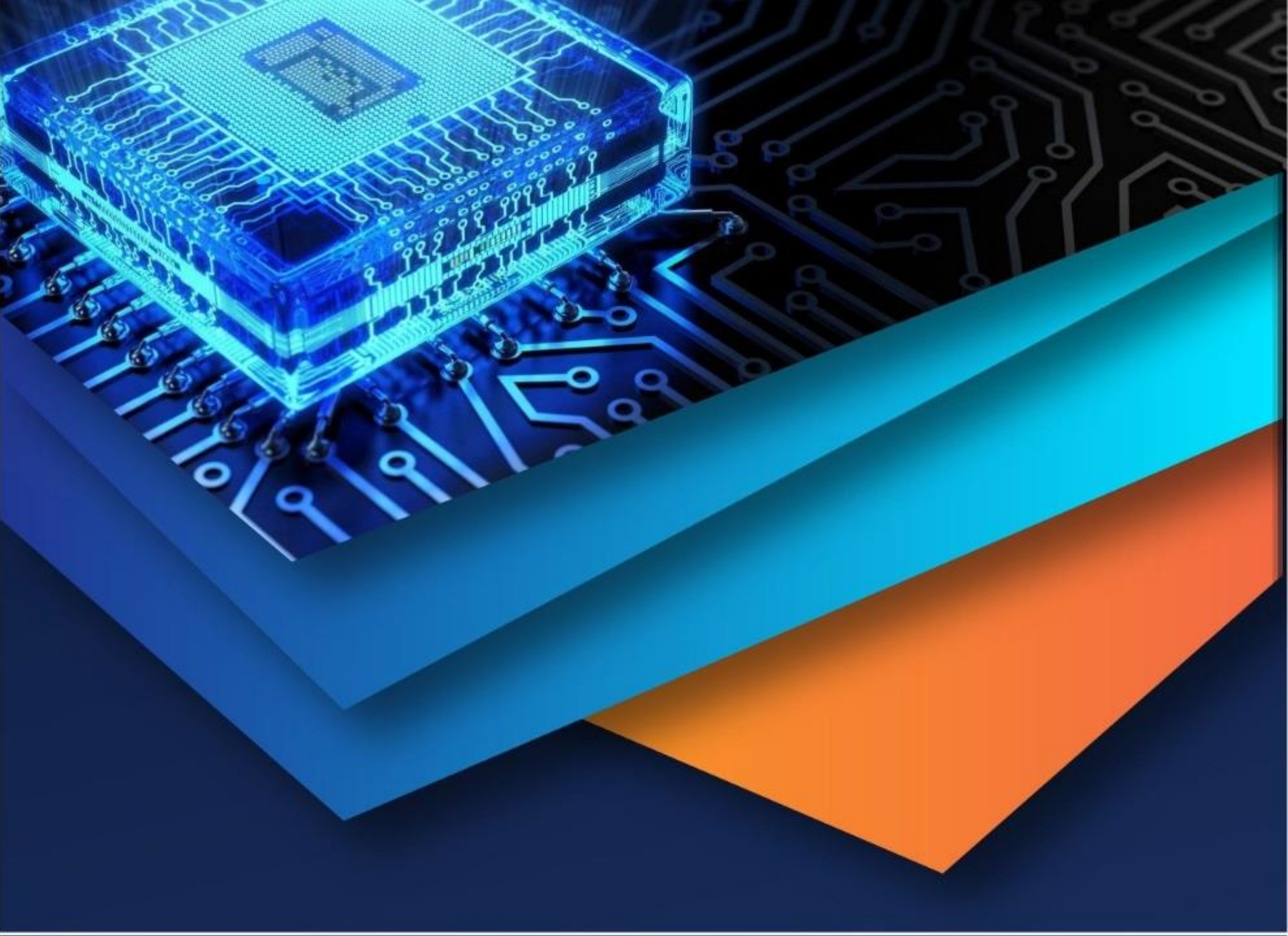

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