A Review of Multi-material and Composite Parts Production by Modified Additive Manufacturing Methods

M. Toursangsaraki

a State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract

Aside from the capability of additive manufacturing (AM) methods in fabricating components with complex geometries, two crucial potentials of this manufacturing process that are worth mentioning are its flexibility in being combined with other production methods as well as use of a variety of materials in a single production platform to make multi-material and composite products. Implementation of multiple materials in integrated structures has been shown to improve the functionality, weight reduction and, by merging the assembly and production into one stage, modify the manufacturing processes. Different approaches towards modification of AM processes aimed to reach multi-material or composite parts are being reviewed in this paper.

Keywords: Multi-material, additive manufacturing, composite.
Contents

1. Introduction ................................................................................................................................. 3
2. Multi-material and composite additive manufacturing methods .................................................. 3
   2.1. Stereolithography methods ................................................................................................. 3
   2.2. Binder jetting methods ....................................................................................................... 4
   2.3. Extrusion based printing methods ....................................................................................... 5
   2.4. Material jetting printing methods ....................................................................................... 6
   2.5. Metallic alloys and FGMs AM techniques ......................................................................... 8
       2.5.1. Powder bed fusion methods ....................................................................................... 8
       2.5.2. Directed energy deposition (DED) methods ............................................................. 8
       2.5.3. Laminating metallic parts ........................................................................................... 9
3. Hybrid applications .................................................................................................................... 9
   3.1. Bioprinting methods .......................................................................................................... 10
   3.2. Shape deposition methods .................................................................................................. 10
       3.3. 3D printed drug delivery systems ................................................................................. 11
       3.4. Electronics embedded 3d printed components ............................................................. 13
4. Summary and Conclusions ........................................................................................................ 17
5. References .................................................................................................................................. 17
1. Introduction

A unique feature of Additive Manufacturing (AM) technology is production capability of multi-material parts. In this approach, multiple types of materials can be used for fabrication of a single part. Components with specially tailored functionally graded, heterogeneous or porous structures and composite materials have been some of the achievements of this method [1-3]. A wide range of materials such as metals, plastics, and ceramics has been used in various AM methods to obtain multi-material products in order to match the current requirements of the industry which wouldn’t be gained otherwise. All the AM techniques have the potential of being applied to multiple material manufacturing in nature. Moreover, many studies have been performed to investigate the possibility of applying multi-material production for different AM methods [4, 5]. The process of making composite materials by AM can either be performed during the material deposition process or by a hybrid process in which the combination of different materials can be performed before or after AM as a previous or subsequent stage of production of a component. Composite processes can be implemented to produce heterogeneous scaffolds and functionally graded materials (FGM). Production of tailor-made gradient multi-phase or porous materials is one of the features of AM processes. As a result, different properties can be achieved within one single integrated part. Furthermore, in making a component with composite materials, the required properties of included materials can be combined while compensating for some of their restrictions.

2. Multi-material and composite additive manufacturing methods

Different modifications of AM and combination of them with other manufacturing methods aimed to generate multi-material or composite products have been listed below. The subjects are mostly categorized by the process adaptations to implement multi-materials, different materials being used in these processes, and hybrids of AM and other manufacturing methods.

2.1. Stereolithography methods

Stereolithography (SLA) has been developed based on photopolymerization phenomena and mostly involves implementing a light source to bond photo-curable resins mixed with other materials to manufacture solid composite parts [6, 7]. Multi material SLA processes have been performed by successively applying and washing off different kinds of photopolymerizable resins in single or multiple vat setups (Fig 1.a) to fabricate each piece of the component with the specific desired materials. The functionality of these approaches has been spread in several fields from fabricating electronic parts to biomedical implants [1, 8-10].

The liquid precursor infiltration method has been typically performed for production of ceramics and their composites. In this method, a porous component is immersed in a liquid infiltration
material. As a result of infiltration of the precursor into the pores of the ceramic component, a wide variety of microstructures such as gradient, partially or fully dense materials as well as an increase in density and mechanical properties of the powder compact can be achieved [11, 12]. In SLA of ceramic materials, a ceramic suspension including photocurable liquid resin is used to produce the green part in the desired shape. Drying and other debinding processes are then implemented to achieve a component with high density and minimal defects [13]. Liu et al. [14] performed an infiltration process after SLA of alumina ceramics by immersing the printed products into liquids of different modifying components to make a multi-phase composite by filling the interconnected porosities with infiltrated materials. A photo-initiator material was added to alumina suspension to make it UV-curable and suitable for SLA process. Debinding and subsequent infiltration were followed by a precipitation process (Fig 1.b). As a result of the infiltration process, an increase in the hardness of the part but a decrease in fracture toughness was reported.

Fig 1. (a) Multiple vat setup for stereolithography of multi-material parts [10], (b) SLA followed by infiltration and precipitation process [14].

2.2. Binder jetting methods

Binder jet printing deposits binder materials on powder bed to selectively join powder materials layer by layer to construct three-dimensional parts [15, 16]. In binder jetting, additional extractable powder materials can be engineered in the binding process to reach a desired percentage of materials in different layers of parts. Then by the use of extraction procedures such as solvent materials, additional materials can be removed to obtain a desired porous or functionally graded material (FGM) product [17].

Applying infiltration processes to ceramic materials produced by AM has been utilized to create multiphase composites. As for the binder jet process, the process uses the nature of porous products of binder jetting. While the binder material is cured to achieve a solid part, they burn off and leave porosities in the final component. The main purpose of infiltration procedure is to fill the porosities with other functional materials to achieve a fully dense part [18, 19]. Ceramic-metallic composites can be produced by binder jetting the ceramic powder materials, curing and
sintering them in specific conditions in order to achieve a solid homogeneous structure and
immersing them in a molten metal bath to fill the porosities with metal. The sintering
temperature of the printed ceramic part can affect the density and volume fraction of metal phase
and consequently microstructure and mechanical properties of the final part [20]. The
submerging time of sintered ceramic part in the molten metal is another discussable parameter
that can change the properties of the products as the more sintered ceramic parts are held in
molten metal, apart from infiltration process, more metallic material permeates into the ceramic
particles and the properties of the products will have higher similarity to the pure metallic parts
made of the molten material [21]. This methodology has also been used for fabrication of
metallic composites. In one study, it has been illustrated that the layer thickness of printed part
has a crucial effect on different properties of the final part as it changes the microstructure and
chemical composition of the product [22].

2.3. Extrusion-based printing methods
Extrusion-based AM uses an extrusion nozzle to deposit materials on a substrate to print the
desired component layer by layer. Low-temperature deposition manufacturing (LDM) is an
extrusion-base AM method which is capable of manufacturing multi-material components with
custom-built porosities (Fig 2). Because LDM process is operated at low temperature, the
bioactivity and biocompatibility of biomaterials can be preserved. This process is capable of
manufacturing scaffolds with functionally graded or composite materials. Biomaterial scaffolds
made of synthetic and natural polymers in tissue engineering applications such as scaffolds
mimicking bone and cartilage structure or nerve and vascular tissues are the main focus of this
fabrication technique [23, 24]. The procedure typically includes depositing the mixture of
materials on an ultra-low temperature platform by a sterilized syringe followed by a freeze-
drying process to remove the solvent material and diminish micropores generated by phase
separation. LDM made scaffolds with core-shell composite framework have been created to
improve their mechanical and physiochemical properties. An inner and outer feedstock tube and
nozzle head were assembled together to extrude the core and the sheath material simultaneously
[25]. A multi-nozzle LDM system using disposable syringes has been applied in order to
fabricate scaffolds with gradient biomaterials and functions for tissue engineering [26, 27].
Fused deposition modeling (FDM) uses filaments containing thermoplastic polymers which are melted and extruded through a nozzle on the desired substrate layer by layer. One of the polymers being fabricated by this method is polyvinylidene fluoride (PVDF), which application has been expanded recently in energy harvesting systems [28]. In FDM of ceramic AM, a composite of polymer and ceramic can be used as the feedstock material to improve the physical and mechanical properties of the final component [29, 30]. Kalita et al. [31] implemented FDM to fabricate composite scaffolds of PP and TCP with tailored interconnected porosities. Different scaffold architectures and the compatibility of the scaffold materials for vitro cell culture were evaluated and the results indicated the ability of the process to manufacture biomaterial components. The integrity and uniformity of the composite filament for the extrusion process is a pivotal factor in accomplishing the desired properties of the products. Other AM-related parameters such as raster gap and width as well as slice thickness are effective in the scaffold structure and, hence, mechanical properties and dispersion of porosities.

The use of sacrificial polymeric mixture or UV curable resins combined with ceramic particles is common in many AM methods of ceramic components production. The additive mixtures roles as a binder in the AM process to produce a green product and gets removed from the part by a subsequent debinding process. However, every single of these approaches usually suffers from its own certain obstacles such as excessive material consumption, low density after sintering, need for additional steps, lack of functionality and limitations in the produced component dimensions. An addition of photopolymerizable dispersion to the raw material of the extrusion-based AM has been tried to take advantage of the steadiness of the green product with UV-cured resin and economical syringe-base AM process. The UV-light irradiation is implemented during the printed process and UV-resin is removed by a typical sintering process. However, deficiencies such as partial polymerization of the layers and cracking of the part due to high shrinkage ratio and during sintering are yet to be dealt with [32].

2.4. Material jetting printing methods

The principals of ink-jet printing (IJP) typically include deposition of a jet stream of droplets or particles of materials, so the materials can fuse and bond together [33, 34]. Different actuating systems for ejection of droplets have been investigated including thermal bubble method, piezoelectric nozzle head, pneumatic diaphragm actuator, and the use of the electrical field to generate ink flow [35, 36]. The application of multiple nozzles or mixing raw materials for printing in the print head, allow the production of multi-material, multiphase composites and FG materials [37-39]. A combination of tape casting technique and IJP has been applied to fabricate electrolyte and electrode of micro-batteries [40, 41]. Flexible supercapacitors have been fabricated by IJP of graphene-based materials on metal films [42]. Ink-jetted dielectrics have also been performed to print insulators for packaging of electronic embedding devices [43] and securing metallic materials crossovers [44]. IJP has been utilized to deposit photoactive materials.
layer for solar cells [45] and multiple materials of photodetectors, both attempts in a combination of applications such as spin coating deposition method [46]. A combination of reverse offset printing, IJP and bar coating was performed for fabrication of flexible phototransistor. In this method, IJP is responsible for polymeric active semiconductor and conductive polymer for gate electrodes [47].

Multi-jet modeling (MJM), also known as material jetting system or poly-jet printing of materials, uses multiple jet nozzles to deposit photopolymers for the part structures, which are immediately cured after the deposition, and gel-like wax materials for the sacrificial support structures [48, 49]. A schematic depiction of the process is shown in Fig 3. This AM technique has the capability to fabricate components with higher resolutions and geometrical complexity such as microfluidic devices with narrow gaps and high-aspect ratios [50-52].

![Fig 3. Schematic of poly-jet 3D printing [53]](image)

Implementing electrospinning technique in syringe-base AM production has been performed in order to reach micro/nano-scale fiber diameters. Utilizing electrospinning in biomaterial AM fabrication methods can lead to better mechanical and biological properties and promote cell proliferation within the tissue engineering scaffolds [54-57]. Some of the limitations of electrospinning methods such as buckling and coiling of the jet stream have been overcome by performing hybrid process with melt-electrospinning [57, 58]. A Combination of syringe-based AM and wet-spinning process, which includes extruding a polymer mixture filament into a precipitating bath to solidify and produce continuous composite fibers, has been performed to produce microfibers for microporous composite scaffolds [59-61]. Because there is no need for high temperature, high voltage or toxic solvents, wet spinning allows for the production of fibers including biomolecules, which makes it suitable for bioprinting. Fig 4 illustrates the setup of electro-spinning and wet-spinning processes.
2.5. Metallic alloys and functionally graded materials (FGM) AM techniques

2.5.1. Powder bed fusion methods

The use of laser or electron beam energy source to selectively melt or sinter powder materials to join them together layer by layer is another AM method called powder bed fusion technique mainly including Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Electron Beam Melting (EBM) [62-66]. This technique is capable of processing metals, ceramic and polymers [67-69]. Fabrication of multi-material products and functionally graded materials, which mechanical properties varies continuously through the thickness of the fabricated sample based on a known exponential function, is usually performed by using multiple chambers with different powder materials to be deposited on different layers in order to make the desired FGM component [70-74].

2.5.2. Directed energy deposition (DED) methods

Directed energy deposition (DED) uses a focused energy source to melt and deposit feedstock. The heat source used in DED process is usually provided by laser, electron beam or electric arc. Moreover, powdered or wired materials are typically used as feedstock materials. This process has been primarily implemented for the metallic parts production [75-77]. Production of bimetal of steel and bronze has been performed by use of Gas Metal Arc Welding (GMAW) to melt and deposit steel and bronze wired materials [77]. For DED of metallic alloys or composites, pre-alloyed feedstock materials are typically used. However, the desired compositions could be achieved by mixing the elemental powders with adjustable fractions during the process. The elemental powder materials can be pre-mixed and fed through a single powder feeder [78] or be fed separately from multiple coaxial power feeders with independently controllable feed rates that lead the various powder flows to converge to the melting point and be deposited on the substrate [79, 80]. The latter is suitable for the production of functionally graded composites, which is used in spacecraft multilayered structures [79, 81-84]. Fig 5 illustrate schematics of multi-chamber SLS and multi-nozzle DED.
2.5.3. Laminating metallic parts

In Laminated Object Manufacturing (LOM), three-dimensional components are fabricated by a combination of forming and lamination of sheets layer by layer. In LOM of metallic parts, laser or mechanical cutters are usually used for forming sheets and bonding process of different layers of sheet materials is achieved by chemical adhesives, thermal bonding, or brazing and welding approaches. Then a finish machining process is applied to achieve the desired geometrical accuracy and surface finish [87, 88].

Ultrasonic welding (UC), a solid-state metal seam welding method, has been widely utilized for sheet metal lamination methods. In this process, an energy produced by an ultrasonic transducer is transferred to the thin metal foils, which are deposited layer by layer, by a rotating sonotrode. The sonotrode travels on the upper surface of the component and oscillates in the vertical direction with high frequency and low amplitude causing diffusion of metal atoms at the sheets’ interface and bond them together [89, 90]. Due to the low-temperature operation of UC process, production of metallic multi-material FGM [91-93], metal matrix composites [94-97], and structures with embedded electronics [98] are possible.

Friction welding and friction stir welding are two kinds of solid-state welding methods which have been widely used for welding of similar and dissimilar metallic materials [99-101]. These processes allow for layer-wise lamination of metallic parts which is then followed by a machining process to shape the layers and produce the desired three-dimensional component [102, 103].

3. Hybrid applications
3.1. Bioprinting methods

Bioprinting technique is usually referred to as a hybrid process that allows printing of tailored structures including multiple cells and biomaterials in a single part [104, 105]. IJP, extrusion-based printing and laser-aided printing are the most common methods used for bioprinting applications. Bioprinting allows for the production of a wide variety of practical biomedical tissues with different shapes and material compositions [106-108]. Fig 6 demonstrates an integrated bioprinting of cells, biomaterials and biological molecules applied for fabrication of tissues and organs.

![Fig 6](image)

**Fig 6.** A schematic of bioprinting of tissues and organs [104].

3.2. Shape deposition methods

As mentioned before, relatively low dimensional accuracy and poor surface finish quality are the two most critical limitations of rapid prototyping methods. The hybrid of subtractive and additive manufacturing has been accomplished to incorporate the design freedom with precision within a fabrication process. Shape deposition manufacturing (SMD) uses a sequence of deposition and subtractive shaping of materials which allows for production and assembly of components at the same time as well as embedding internal parts inside every each component during the process [109, 110]. Having the abilities of the production of multi-material structures with varying material properties and embedding prefabricated components such as electronic parts like sensors and actuators within the components, SDM is capable of processing biomimetic mechanisms such as compliant joints and rigid parts of adaptive and robust robotic limbs [111-114]. An example of polymer-based SDM to produce a heterogeneous monolithic robotic grasper structure as well as a comparison between the SDM made and conventional robotic limb mechanism is shown in Fig 7.
Fig 7. An example of polymer based SDM for production of a heterogeneous monolithic robotic grasper structure (a) and a comparison between the SDM made (b) and conventional robotic limb mechanism (c) [111, 112, 115].

3.3. 3D printed drug delivery systems

The use of 3D printing methods has been widely investigated in the biomedical field such as fabrication of customized prosthetic implants and surgical tools as well as drug delivery systems. The approaches to introduce pharmaceutical ingredients to the body are referred as drug delivery systems. Drug delivery systems have attracted lots of attention recent years, so that many works such as fluid-conveying micro/nano tubes have been carried out in this regard [116-118]. The goal is to transfer the desired amount of therapeutic agents to the planned locations with specific release rates to meet individual needs of patients [119, 120]. 3D printing of pharmaceuticals allows for flexible fabrication of multi-active dosage forms with predefined release profiles as well as an efficient production of on-demand personalized medicines [121-123]. Khaled et al. [124] performed extrusion-based printing for the production of polypills having multiple active components with a certain release profile.

FDM has been widely investigated in 3D printing of pharmaceutical components. Composites of bio-compatible filaments mainly containing PLA or PVA polymers have been predominantly used as raw materials for FDM of drug-carrying units. Several studies have been devoted to investigating capabilities of FDM in the fabrication of hollow structures such as capsular devices and coating layers as well as scaffolds with tailored holes positioned at the side [125, 126]. Moreover, in some studies, approaches like wet-spinning, melt electrospinning and hot melt extrusion (HME) process have been utilized to produce drug loaded filaments as the feedstock of FDM to directly print drug loaded structures [127-130]. Goyanes et al. [131] used a multi-nozzle printer for FDM of multiple drug-loaded filaments to produce drug delivery devices with multi-
active components. Two PVA filaments, one loaded with paracetamol and the other with caffeine, were printed to make a two-part device. Simultaneous and independent drug release profiles of both drug materials were observed in the drug release test.

Binder jet printing has been also performed for drug delivery systems by applying drops of binders to a powder bed consisting of biocompatible polymers or/and active ingredients. Several investigations have been performed in this area to achieve predefined microstructures and programmed drug release profiles via printing structures with bonded regions [132-134]. Pulsatory drug release profile was achieved by tailoring drug distribution at different parts of the drug implants [135] or depositing various compositions of binder materials to confine active materials in different locations [136].

Drop-on-demand (DoD) is an IJP method in which droplets of printing materials are deposited at targeted areas. Being able to operate with a variety of printing solutions with predefined properties on different substrate materials, having robust control over drop deposition dynamics, and the possibility of using multiple nozzles or reservoirs for a single printing process make DoD as a great method for printing pharmaceutical productions with multiple active components. This technique has been applied to several pharmaceutical manufacturing procedures such as drug coating of medical implants like stents and catheters as well as 3D printing of unit doses including active ingredients [137-140]. Gupta et al. [141] applied this method for printing stimuli-responsive capsules with an aqueous core containing biomolecules and polymeric shells, which are selectively ruptured via laser irradiation to achieve a programmable release of the core materials. Fig 8 illustrates different stages of this process including the final printed three-dimensional component. Fabrication of three-dimensional capsule arrays in hierarchical structures with programmable drug release profiles via sequential deposition of biomolecules in aqueous cores was also reported.
Fig 8. (a) Process illustration of three dimensional drug delivery system containing arrays of ink-jet printed capsule, (b) selective rupturing of polymeric shells via laser irradiation, (c) the final printed drug delivery system [141].

3.4. Electronics embedded 3D printed components

Additive manufacturing (AM) techniques allow for integration of other approaches like embedding of active or passive electronic components as well as conductive interconnects to fabricate three-dimensional electronic devices. The main stages of this process consist of printing dielectric structures, which can be manufactured by almost all kinds of AM methods, assembling electronic components performed by hand or pick-and-place robots, and the deposition of conductive traces, which can be done by wire embedding techniques, liquid metal paste injection, and direct writing (DW) methods such as IJP, extrusion-based methods and aerosol jet printing (AJP) [142-144].

Aerosol jet printing is a DW method which deposits an aerodynamically focused gaseous stream of aerosolized ink materials on a substrate. The properties such as adjustable deposition head direction, the ability to deposit at room temperature while maintaining a relatively high stand-off distance from the substrate, and capability of processing all kinds of materials needed for electronic devices make AJP process suitable for printing dielectric materials, semiconductors, conductive traces, and interconnectors on any 3D surface. This allows for 3D printing of components with embedded electronics, solar cells, antennae, sensors, and resistors. A thermal sintering is usually applied as a post-processing step to increase the integration of deposited particles and improve the conductivity [145-147]. Low viscosity inks are the usual raw materials for AJP. Silver nanoparticle suspensions have been used for AJP of conductive interconnectors of electronic chips in several investigations [148]. AJP of composite suspension of carbon nanotubes and silver nanoparticles has been reported for printing traces with improved conductivity [149]. A composition of aerosol printed current collecting grids of silver ink with conductive materials has been utilized for the manufacturing of optoelectronic devices [150]. 3D sub-millimeter structures with a potential to be used as passives and antennas have been manufactured by multi-material AJP of metal nanoparticles on UV curable dielectric materials, which are instantly cured after being dispensed on the substrate [151]. Fabrication of composite film of strontium titanate and alumina with AJP to make semiconducting temperature independent oxygen sensors was reported in [152]. The other advantage of multi-material AJP is the ability to print an intermediate dielectric layer between different conductive traces in the crossover areas [153].

IJP has been proved to be another approach for printing conductive interconnectors of embedded electronic devices. The use of a low-cost ink with proper conductivity, printability, less challenging post-processing demands, and compatibility with the desired substrates are the essential properties of this method [154]. Metal nanoparticles, metal-organic decompositions (MOD) and aqueous conductive solution inks have been investigated for this purpose [155-157].
To obtain the desired conductive patterns, post-printing approaches, such as thermal, photonic, or chemical sintering have been used [158]. Sequential IJP of conductive and dielectric materials has been performed on separate conductive traces in crossover areas [44, 159]. Poly-jet printing is another suitable procedure for printing equipment with embedded electronics like interactive devices [160]. Chang et al. [161] reported print-stick-peel (PSP) for the fabrication of multi-material parts of poly-jet printed components via AJP with embedded strain sensors. To avoid the pauses in the poly-jet printing process, which weakens the bonding between layers and has the adverse effect of thermal sintering of conductive ink on polymer substrates, conductive traces are printed and sintered on another substrate and then transferred to the desired location.

Stereolithography (SLA) has been also investigated in the manufacturing of functional electronics and electronics embedded parts. SLA of photopolymers containing high dielectric particles was performed to manufacture capacitors with complex geometries and certain capacitance [162]. Hybrid of SLA and DW allows for the fabrication of three-dimensional components with embedded electronics and interconnectors. Conductive traces are usually dispensed by extrusion-based printing methods. Connection pins or other conductive vias have been utilized for vertical interconnections in some applications [163-165]. Fig 9 illustrates the main stages of electronics embedded SLA hybrid production.

![Fig 9. The main stages of electronics embedded SLA hybrid production](image)

FDM allows for the printing of thermoplastic materials used in the dielectric structure of three-dimensional electronic embedded parts. Aside from the proper mechanical properties of these components, they do not provide suitable resolution to embed electronic devices or conductive ink materials [166]. Furthermore, channels are needed to be formed on the surface for depositing the interconnect traces to avoid any damages to the ink caused by the deposition of subsequent layers in the process of embedding the electronics. Therefore, often subsequent subtractive methods are required to form the desired features and reach a suitable surface and dimensional quality (Fig 10.a). Thermoplastic dielectric materials also allow for the full embedding of copper wires into the surface of the electrical interconnectors by using thermal processes such as ultrasonic embedding (Fig 10.b). Bulk materials such as wires provide noticeably more electrical conductivity in comparison with the cured metallic inks. Laser micro-welding has been reported in [144] to be a suitable method to join wire interconnectors to the electronic components. In some studies, injection of low melting temperature metallic alloys into the hollow channels of
structures made by FDM was used to fabricate conductive interconnectors. Hollow channels and cavities have been made by either leaving gaps during printing process [167] or by performing multi-nozzle system and printing sacrificial materials in the desired areas for the electric interconnects and removing these materials after the printing process [168] (Fig 10.c).

![Diagram demonstrating the steps of embedding electronic circuits with conductive ink interconnectors](image)

**Fig 10.** (a) Different steps of embedding electronic circuits with conductive ink interconnectors in a FDM dielectric substrate [144], (b) multi-nozzle FDM followed by melted metal injection for conductive parts [168], (c) ultrasonic wire embedding to thermoplastic substrates [169].

Binder jet printing has also been utilized for the dielectric structure of electronic embedded parts with the combination of AJP for printing conductive interconnecting traces. Selectively binding of powder material was performed to shape the three-dimensional structure of the component. Additionally, an exhausting system was applied to remove the powder in unbounded regions to create cavity and channels in order to place electrical parts and dispense interconnector materials [170]. SLS of polymer materials was also integrated with DW methods, including AJP and extrusion-based method of dispensing silver inks, to create conductive traces embedded components [171].

UC allows for fully embedding electronic parts into a solid metallic structure in a relatively low-temperature process. Machining processes can be utilized to create pockets to embed electronic devices as well as interconnectors [172]. The use of DW of silver ink was reported in [173] for printing conductive traces as an antenna for UC electronic embedded parts. The possibility of creating electronic embedded dense metal matrix components was investigated by screen printing of dielectric materials, which have the potential of embedding electronic components into metallic substrates and directly encasing them with UC of metallic foils in a solid part [174, 175]. Fig 11 illustrates these two different kinds of embedding electronics in this process.
Electromechanical systems are the integration of electronics and mechanical parts which either use the electronic signals to trigger movements or generate electronic signals actuated by moving parts. AM of electromechanical systems has the capability of rapid fabrication of structures with complicated and customized shapes and dimensions. A micro-scale bistable vibration energy harvester (VEH) was designed and fabricated by several deposition processes followed by some patterning steps [176]. Aguilera et al. [169] developed a hybrid fabrication method to produce a 3-phase DC motor by five different stages including assembling ball bearings and electrical components, fused deposition of thermoplastic material to subsequently build and encapsulate different parts of the device, wire embedding, and laser micro welding of wires and electrical components for the interconnections (Fig 12.a). Fuller et al. [177] used two and three dimensional IJP of metal nanoparticle colloids to fabricate microelectromechanical systems (MEMS) such as electrothermal actuators and planar cantilevered structures (Fig 12.b).
4. Summary and Conclusions

Different experimental processes including modification of AM and their combinations with other manufacturing processes targeting more efficient production of multi-material and composite products have been reviewed in this study. Several investigated potentials of AM in being combined with other manufacturing processes have been mentioned. Moreover, various functions of these products in different industries including medical devices, electronics, biomedical implementations, and robotics have been summarized. Another purpose of this literature review was to investigate how and in what orders different manufacturing operations can be combined to reach a component with unconventional structures and practicality. For this purpose, AM was considered as the main focus of this study and other additional procedures were mentioned as post-processes, pre-processes or concurrent ones with AM. The immense effects of AM methods in the mentioned areas with their simplicity and flexibility have been observed for the past two decades. However, many potentials of AM methods in manufacturing and design development are still to be investigated.

5. References

1. Zhou, C., et al. Development of multi-material mask-image-projection-based stereolithography for the fabrication of digital materials. in Annual solid freeform fabrication symposium, Austin, TX. 2011.
2. Sugavaneswaran, M. and G. Arumaikkannu, Modelling for randomly oriented multi material additive manufacturing component and its fabrication. Materials & Design (1980-2015), 2014. 54: p. 779-785.
3. Huang, P., D. Deng, and Y. Chen. Modeling and fabrication of heterogeneous three-dimensional objects based on additive manufacturing. in ASME 2013 International Mechanical Engineering Congress and Exposition. 2013. American Society of Mechanical Engineers.
4. Mueller, B., Additive manufacturing technologies–Rapid prototyping to direct digital manufacturing. Assembly Automation, 2012. 32(2).
5. Vaezi, M., et al., Multiple material additive manufacturing–Part 1: a review: this review paper covers a decade of research on multiple material additive manufacturing technologies which can produce complex geometry parts with different materials. Virtual and Physical Prototyping, 2013. 8(1): p. 19-50.
6. Sakly, A., et al., A novel quasicrystal-resin composite for stereolithography. Materials & Design, 2014. 56: p. 280-285.
7. Bártolo, P.J., Stereolithographic processes, in Stereolithography. 2011, Springer. p. 1-36.
8. Raman, R. and R. Bashir, Stereolithographic 3D bioprinting for biomedical applications. Essentials of 3D Biofabrication and Translation, 2015. 89: p. 121.
9. Arcaute, K., B. Mann, and R. Wicker, Stereolithography of spatially controlled multi-material bioactive poly (ethylene glycol) scaffolds. Acta biomaterialia, 2010. 6(3): p. 1047-1054.
10. Wicker, R.B. and E.W. MacDonald, Multi-material, multi-technology stereolithography: This feature article covers a decade of research into tackling one of the major challenges of the stereolithography technique, which is including multiple materials in one construct. Virtual and Physical Prototyping, 2012. 7(3): p. 181-194.
11. Park, H., et al., Preparation of zirconia–mullite composites by an infiltration route. Materials Science and Engineering: A, 2005. 405(1): p. 233-238.
12. Liu, G., Z. Xie, and Y. Wu, Fabrication and mechanical properties of homogeneous zirconia toughened alumina ceramics via cyclic solution infiltration and in situ precipitation. Materials & Design, 2011. 32(6): p. 3440-3447.

13. Zhou, M., et al., Preparation of a defect-free alumina cutting tool via additive manufacturing based on stereolithography—Optimization of the drying and debinding processes. Ceramics international, 2016. 42(10): p. 11598-11602.

14. Liu, W., et al., Fabrication of fine-grained alumina ceramics by a novel process integrating stereolithography and liquid precursor infiltration processing. Ceramics International, 2016. 42(15): p. 17736-17741.

15. Miyanaji, H., S. Zhang, and L. Yang, A new physics-based model for equilibrium saturation determination in binder jetting additive manufacturing process. International Journal of Machine Tools and Manufacture, 2018. 124(Supplement C): p. 1-11.

16. Miyanaji, H., N. Momenzadeh, and L. Yang, Effect of printing speed on quality of printed parts in Binder Jetting Process. Additive Manufacturing, 2018. 20: p. 1-10.

17. Sherwood, J.K., et al., A three-dimensional osteochondral composite scaffold for articular cartilage repair. Biomaterials, 2002. 23(24): p. 4739-4751.

18. Moon, J., et al., Fabrication of functionally graded reaction infiltrated SiC–Si composite by three-dimensional printing (3DP™) process. Materials Science and Engineering: A, 2001. 298(1-2): p. 110-119.

19. Melcher, R., et al., Fabrication of Al2O3-based composites by indirect 3D-printing. Materials Letters, 2006. 60(4): p. 572-575.

20. Myers, K., et al., Mechanical modeling based on numerical homogenization of an Al2O3/Al composite manufactured via binder jet printing. Computational Materials Science, 2015. 108: p. 128-135.

21. Myers, K., et al., Structure property relationship of metal matrix syntactic foams manufactured by a binder jet printing process. Additive Manufacturing, 2015. 5: p. 54-59.

22. Doyle, M., et al., Effect of layer thickness and orientation on mechanical behavior of binder jet stainless steel 420+ bronze parts. Procedia Manufacturing, 2015. 1: p. 251-262.

23. Liu, W., et al., Low-temperature deposition manufacturing: A novel and promising rapid prototyping technology for the fabrication of tissue-engineered scaffold. Materials Science and Engineering: C, 2017. 70: p. 976-982.

24. Xu, M., et al., Fabricating a pearl/PLGA composite scaffold by the low-temperature deposition manufacturing technique for bone tissue engineering. Biofabrication, 2010. 2(2): p. 025002.

25. Wang, C., et al., Physical properties and biocompatibility of a core-sheath structure composite scaffold for bone tissue engineering in vitro. BioMed Research International, 2012. 2012.

26. Liu, L., et al., Multinozzle low-temperature deposition system for construction of gradient tissue engineering scaffolds. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 2009. 88(1): p. 254-263.

27. Liu, L., et al., A novel osteochondral scaffold fabricated via multi-nozzle low-temperature deposition manufacturing. Journal of Bioactive and Compatible Polymers, 2009. 24(1_suppl): p. 18-30.

28. Derakhshani, M., T. Berfield, and K.D. Murphy, Dynamic Analysis of a Bi-stable Buckled Structure for Vibration Energy Harvester, in Dynamic Behavior of Materials, Volume 1. 2018, Springer. p. 199-208.

29. Venkataraman, N., et al., Feedstock material property–process relationships in fused deposition of ceramics (FDC). Rapid Prototyping Journal, 2000. 6(4): p. 244-253.

30. Lous, G.M., et al., Fabrication of piezoelectric ceramic/polymer composite transducers using fused deposition of ceramics. Journal of the American Ceramic Society, 2000. 83(1): p. 124-28.

31. Kalita, S.J., et al., Development of controlled porosity polymer-ceramic composite scaffolds via fused deposition modeling. Materials Science and Engineering: C, 2003. 23(5): p. 611-620.
32. Faes, M., et al., *Extrusion-based additive manufacturing of ZrO 2 using photoinitiated polymerization*. CIRP Journal of Manufacturing Science and Technology, 2016. 14: p. 28-34.
33. Murr, L.E., *Frontiers of 3D printing/additive manufacturing: from human organs to aircraft fabrication*. Journal of Materials Science & Technology, 2016. 32(10): p. 987-995.
34. Ko, S.H., et al., *Metal nanoparticle direct inkjet printing for low-temperature 3D micro metal structure fabrication*. Journal of Micromechanics and Microengineering, 2010. 20(12): p. 125010.
35. Xie, D., et al., *Multi-materials drop-on-demand inkjet technology based on pneumatic diaphragm actuator*. Science China Technological Sciences, 2010. 53(6): p. 1605-1611.
36. Qin, H., J. Dong, and Y.-S. Lee, *AC-pulse modulated electrohydrodynamic jet printing and electroless copper deposition for conductive microscale patterning on flexible insulating substrates*. Robotics and Computer-Integrated Manufacturing, 2017. 43: p. 179-187.
37. Ibrahim, M., et al., *Inkjet printing resolution study for multi-material rapid prototyping*. JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, 2006. 49(2): p. 353-360.
38. Wang, J. and L.L. Shaw, *Fabrication of functionally graded materials via inkjet color printing*. Journal of the American Ceramic Society, 2006. 89(10): p. 3285-3289.
39. Li, L., et al., *Development of a multi-nozzle drop-on-demand system for multi-material dispensing*. Journal of Materials Processing Technology, 2009. 209(9): p. 4444-4448.
40. Delannoy, P.-E., et al., *Ink-jet printed porous composite LiFePO 4 electrode from aqueous suspension for microbatteries*. Journal of Power Sources, 2015. 287: p. 261-268.
41. Delannoy, P.-E., et al., *Toward fast and cost-effective ink-jet printing of solid electrolyte for lithium microbatteries*. Journal of Power Sources, 2015. 274: p. 1085-1090.
42. Ervin, M.H., L.T. Le, and W.Y. Lee, *Inkjet-printed flexible graphene-based supercapacitor*. Electrochimica Acta, 2014. 147: p. 610-616.
43. Mengel, M. and I. Nikitin, *Inkjet printed dielectrics for electronic packaging of chip embedding modules*. Microelectronic Engineering, 2010. 87(4): p. 593-596.
44. Sanchez-Romaguera, V., M.-B. Madec, and S.G. Yeates, *Inkjet printing of 3D metal–insulator–metal crossovers*. Reactive and Functional Polymers, 2008. 68(6): p. 1052-1058.
45. Haldar, A., K.-S. Liao, and S.A. Curran, *Fabrication of inkjet printed organic photovoltaics on flexible Ag electrode with additives*. Solar Energy Materials and Solar Cells, 2014. 125: p. 283-290.
46. Grimoldi, A., et al., *Inkjet printed polymeric electron blocking and surface energy modifying layer for low dark current organic photodetectors*. Organic Electronics, 2016. 36: p. 29-34.
47. Kim, M., et al., *Flexible organic phototransistors based on a combination of printing methods*. Organic Electronics, 2014. 15(11): p. 2677-2684.
48. Kim, H., Y. Zhao, and L. Zhao. *Process-level modeling and simulation for HP's Multi Jet Fusion 3D printing technology*. in Cyber-Physical Production Systems (CPPS), 2016 1st International Workshop on. 2016. IEEE.
49. Gardan, J., *Additive manufacturing technologies: state of the art and trends*. International Journal of Production Research, 2016. 54(10): p. 3118-3132.
50. Zhu, F., et al., *Three-dimensional printed millifluidic devices for zebrafish embryo tests*. Biomicrofluidics, 2015. 9(4): p. 046502.
51. Sochol, R., et al., *3D printed microfluidic circuitry via multijet-based additive manufacturing*. Lab on a Chip, 2016. 16(4): p. 668-678.
52. Choi, J.-W., et al., *Combined micro and macro additive manufacturing of a swirling flow coaxial phacoemulsifier sleeve with internal micro-vanes*. Biomedical microdevices, 2010. 12(5): p. 875-886.
53. ; Available from: http://www.slideshare.net/radtechvueb/multimaterial-3d-printing.
54. Xu, T., et al., *Hybrid printing of mechanically and biologically improved constructs for cartilage tissue engineering applications*. Biofabrication, 2012. 5(1): p. 015001.
55. Pham, Q.P., U. Sharma, and A.G. Mikos, Electrospinning of polymeric nanofibers for tissue engineering applications: a review. Tissue engineering, 2006. 12(5): p. 1197-1211.

56. Kang, Y.G., et al., A three-dimensional hierarchical scaffold fabricated by a combined rapid prototyping technique and electrospinning process to expand hematopoietic stem/progenitor cells. Biotechnology letters, 2016. 38(1): p. 175-181.

57. Garrigues, N.W., et al., Electrospun cartilage-derived matrix scaffolds for cartilage tissue engineering. Journal of biomedical materials research Part A, 2014. 102(11): p. 3998-4008.

58. Brown, T.D., et al., Melt electrospinning of poly (ε-caprolactone) scaffolds: Phenomenological observations associated with collection and direct writing. Materials Science and Engineering: C, 2014. 45: p. 698-708.

59. Mota, C., et al., Additive manufacturing of star poly (ε-caprolactone) wet-spun scaffolds for bone tissue engineering applications. Journal of Bioactive and Compatible Polymers, 2013. 28(4): p. 320-340.

60. Arafat, M.T., et al., Biomimetic wet-stable fibres via wet spinning and diacid-based crosslinking of collagen triple helices. Polymer, 2015. 77: p. 102-112.

61. Salomão, R. and J. Brandi, Macrostructures with hierarchical porosity produced from alumina–aluminum hydroxide–chitosan wet-spun fibers. Ceramics International, 2013. 39(7): p. 8227-8235.

62. Bhavar, V., et al. A review on powder bed fusion technology of metal additive manufacturing. in 4th International Conference and Exhibition on Additive Manufacturing Technologies-AM-2014, September. 2014.

63. Wood, B.M., 5 Multifunctionality in Additive Manufacturing. Design and Manufacture of Plastic Components for Multifunctionality: Structural Composites, Injection Molding, and 3D Printing, 2015: p. 171.

64. Imani, F., et al. Fractal pattern recognition of image profiles for manufacturing process monitoring and control. in International Manufacturing Science and Engineering Conference. 2018.

65. Yao, B., et al., Multifractal Analysis of Image Profiles for the Characterization and Detection of Defects in Additive Manufacturing. Journal of Manufacturing Science and Engineering, 2018. 140(3): p. 031014.

66. Yao, B., F. Imani, and H. Yang, Markov Decision Process for Image-guided Additive Manufacturing. IEEE Robotics and Automation Letters, 2018.

67. Sing, S.L., et al., Laser and electron-beam powder-bed additive manufacturing of metallic implants: A review on processes, materials and designs. Journal of Orthopaedic Research, 2016. 34(3): p. 369-385.

68. Travitzky, N., et al., Additive Manufacturing of Ceramic-Based Materials. Advanced Engineering Materials, 2014. 16(6): p. 729-754.

69. Drexler, M., M. Lexow, and D. Drummer, Selective Laser Melting of Polymer Powder–Part mechanics as function of exposure speed. Physics Procedia, 2015. 78: p. 328-336.

70. Liu, Z., et al., Interfacial characterization of SLM parts in multi-material processing: Metallurgical diffusion between 316L stainless steel and C18400 copper alloy. Materials Characterization, 2014. 94: p. 116-125.

71. Hosseini-Hashemi, S., M. Derakhshani, and M. Fadaee, An accurate mathematical study on the free vibration of stepped thickness circular/annular Mindlin functionally graded plates. Applied Mathematical Modelling, 2013. 37(6): p. 4147-4164.

72. Terrazas, C.A., et al., Multi-material metallic structure fabrication using electron beam melting. The International Journal of Advanced Manufacturing Technology, 2014. 71(1-4): p. 33-45.

73. Sing, S., et al., Interfacial characterization of SLM parts in multi-material processing: Intermetallic phase formation between AlSi10Mg and C18400 copper alloy. Materials Characterization, 2015. 107: p. 220-227.
74. Mumtaz, K.A. and N. Hopkinson, *Laser melting functionally graded composition of Waspaloy® and Zirconia powders*. Journal of Materials Science, 2007. 42(18): p. 7647-7656.
75. Gibson, I., D.W. Rosen, and B. Stucker, *Additive manufacturing technologies*. Vol. 238. 2010: Springer.
76. Thompson, S.M., et al., *An overview of Direct Laser Deposition for additive manufacturing: Part I: Transport phenomena, modeling and diagnostics*. Additive Manufacturing, 2015. 8: p. 36-62.
77. Sames, W.J., et al., *The metallurgy and processing science of metal additive manufacturing*. International Materials Reviews, 2016. 61(5): p. 315-360.
78. Yan, L., et al., *Direct laser deposition of Ti-6Al-4V from elemental powder blends*. Rapid Prototyping Journal, 2016. 22(5): p. 810-816.
79. Collins, P., et al., *Laser deposition of compositionally graded titanium–vanadium and titanium–molybdenum alloys*. Materials Science and Engineering: A, 2003. 352(1): p. 118-128.
80. Domack, M. and J. Baughman, *Development of nickel-titanium graded composition components*. Rapid Prototyping Journal, 2005. 11(1): p. 41-51.
81. Krishna, B.V., et al., *Functionally graded Co–Cr–Mo coating on Ti–6Al–4V alloy structures*. Acta Biomaterialia, 2008. 4(3): p. 697-706.
82. Hofmann, D.C., et al., *Developing gradient metal alloys through radial deposition additive manufacturing*. Scientific reports, 2014. 4.
83. Sahasrabudhe, H., et al., *Stainless steel to titanium bimetallic structure using LENS™*. Additive Manufacturing, 2015. 5: p. 1-8.
84. Derakhshani, M., S. Hosseini-Hashemi, and M. Fadaee, *An analytical closed-form solution for free vibration of stepped circular/annular Mindlin functionally graded plate*. arXiv preprint arXiv:1804.10583, 2018.
85. Beal, V., et al. *Fabrication of x-graded H13 and Cu powder mix using high power pulsed Nd: YAG laser*. in Proceedings of Solid freeform fabrication symposium, Austin, Texas, USA. 2004.
86. Schwendner, K.I., et al., *Direct laser deposition of alloys from elemental powder blends*. Scripta Materialia, 2001. 45(10): p. 1123-1129.
87. Wimpenny, D.I., B. Bryden, and I.R. Pashby, *Rapid laminated tooling*. Journal of Materials Processing Technology, 2003. 138(1): p. 214-218.
88. Park, J., M.J. Tari, and H.T. Hahn, *Characterization of the laminated object manufacturing (LOM) process*. Rapid Prototyping Journal, 2000. 6(1): p. 36-50.
89. Pal, D. and B. Stucker, *A study of subgrain formation in Al 3003 H-18 foils undergoing ultrasonic additive manufacturing using a dislocation density based crystal plasticity finite element framework*. Journal of Applied Physics, 2013. 113(20): p. 203517.
90. Dehoff, R. and S. Babu, *Characterization of interfacial microstructures in 3003 aluminum alloy blocks fabricated by ultrasonic additive manufacturing*. Acta Materialia, 2010. 58(13): p. 4305-4315.
91. Obielodan, J., et al., *Multi-material bonding in ultrasonic consolidation*. Rapid prototyping journal, 2010. 16(3): p. 180-188.
92. Obielodan, J. and B. Stucker, *A fabrication methodology for dual-material engineering structures using ultrasonic additive manufacturing*. The International Journal of Advanced Manufacturing Technology, 2014. 70(1-4): p. 277-284.
93. Hopkins, C., M. Dapino, and S. Fernandez, *Statistical characterization of ultrasonic additive manufacturing Ti/Al composites*. Journal of Engineering Materials and Technology, 2010. 132(4): p. 041006.
94. Li, D. and R.C. Soar, *Characterization of process for embedding SiC fibers in Al 6061 O matrix through ultrasonic consolidation*. Journal of Engineering Materials and Technology, 2009. 131(2): p. 021016.
95. Yang, Y., B. Stucker, and G. Janaki Ram, *Mechanical properties and microstructures of SiC fiber-reinforced metal matrix composites made using ultrasonic consolidation*. Journal of composite materials, 2010. 44(26): p. 3179-3194.
96. Hahnlen, R. and M.J. Dapino, NiTi–Al interface strength in ultrasonic additive manufacturing composites. Composites Part B: Engineering, 2014. 59: p. 101-108.

97. Hehr, A. and M.J. Dapino, Interfacial shear strength estimates of NiTi–Al matrix composites fabricated via ultrasonic additive manufacturing. Composites Part B: Engineering, 2015. 77: p. 199-208.

98. Friel, R.J. and R.A. Harris, Ultrasonic additive manufacturing—a hybrid production process for novel functional products. Procedia CIRP, 2013. 6: p. 35-40.

99. Satyanarayana, V., G.M. Reddy, and T. Mohandas, Dissimilar metal friction welding of austenitic–ferritic stainless steels. Journal of Materials Processing Technology, 2005. 160(2): p. 128-137.

100. Bisadi, H., et al., The influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and commercially pure copper sheets lap joints. Materials & Design, 2013. 43: p. 80-88.

101. Bisadi, H., M. Tour, and A. Tavakoli, The influence of process parameters on microstructure and mechanical properties of friction stir welded Al 5083 alloy lap joint. American journal of Materials science, 2011. 1(2): p. 93-97.

102. Palanivel, S., H. Sidhar, and R. Mishra, Friction stir additive manufacturing: Route to high structural performance. JOM, 2015. 67(3): p. 616-621.

103. Dilip, J., et al., Use of friction surfacing for additive manufacturing. Materials and Manufacturing Processes, 2013. 28(2): p. 189-194.

104. Seol, Y.-J., et al., Bioprinting technology and its applications. European Journal of Cardio-Thoracic Surgery, 2014. 46(3): p. 342-348.

105. Visser, J., et al., Biofabrication of multi-material anatomically shaped tissue constructs. Biofabrication, 2013. 5(3): p. 035007.

106. Murphy, S.V. and A. Atala, 3D bioprinting of tissues and organs. Nature biotechnology, 2014. 32(8): p. 773-785.

107. Lee, V.K., et al., Creating perfused functional vascular channels using 3D bio-printing technology. Biomaterials, 2014. 35(28): p. 8092-8102.

108. Kumar, A., et al., Low temperature additive manufacturing of three dimensional scaffolds for bone-tissue engineering applications: Processing related challenges and property assessment. Materials Science and Engineering: R: Reports, 2016. 103: p. 1-39.

109. Suresh, S.A., et al., Surface and shape deposition manufacturing for the fabrication of a curved surface gripper. Journal of Mechanisms and Robotics, 2015. 7(2): p. 021005.

110. Chua, C.K., K.F. Leong, and C.S. Lim, Rapid Prototyping: Principles and Applications2nd Edition (with Companion CD-ROM). Vol. 1. 2003: World Scientific Publishing Co Inc.

111. Gafford, J., et al., Shape deposition manufacturing of a soft, atraumatic, and deployable surgical grasper. Journal of Mechanisms and Robotics, 2015. 7(2): p. 021006.

112. Bailey, S.A., et al. Biomimetic robotic mechanisms via shape deposition manufacturing. in Robotics Research: The Ninth International Symposium. 1999.

113. Dollar, A.M. and R.D. Howe. The SDM hand as a prosthetic terminal device: a feasibility study. in Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on. 2007. IEEE.

114. Cham, J.G., et al., Fast and robust: Hexapedal robots via shape deposition manufacturing. The International Journal of Robotics Research, 2002. 21(10-11): p. 869-882.

115. Dollar, A.M. and R.D. Howe, Design and evaluation of a robust compliant grasper using shape deposition manufacturing. in Proceedings of the ASME Design Engineering Technical Conference. 2005.

116. Ghasemi, A., M. Dardel, and M.H. Ghasemi, Collective Effect of Fluid's Coriolis Force and Nanoscale's Parameter on Instability Pattern and Vibration Characteristic of Fluid-Conveying Carbon Nanotubes. Journal of Pressure Vessel Technology, 2015. 137(3): p. 031301.
117. Ghasemi, A., M. Dardel, and M.H. Ghasemi, Control of the non-linear static deflection experienced by a fluid-carrying double-walled carbon nanotube using an external distributed load. Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanoengineering and Nanosystems, 2012. 226(4): p. 181-190.

118. Ghasemi, A., et al., Analytical analysis of buckling and post-buckling of fluid conveying multi-walled carbon nanotubes. Applied Mathematical Modelling, 2013. 37(7): p. 4972-4992.

119. Giannatsis, J. and V. Dedoussis, Additive fabrication technologies applied to medicine and health care: a review. The International Journal of Advanced Manufacturing Technology, 2009. 40(1): p. 116-127.

120. Paolino, D., et al., Drug delivery systems. Encyclopedia of medical devices and instrumentation, 2006.

121. Goole, J. and K. Amighi, 3D printing in pharmaceutics: a new tool for designing customized drug delivery systems. International journal of pharmaceutics, 2016. 499(1): p. 376-394.

122. Norman, J., et al., A new chapter in pharmaceutical manufacturing: 3D-printed drug products. Advanced drug delivery reviews, 2017. 108: p. 39-50.

123. Prasad, L.K. and H. Smyth, 3D Printing technologies for drug delivery: a review. Drug delivery and industrial pharmacy, 2016. 42(7): p. 1019-1031.

124. Khaled, S.A., et al., 3D printing of tablets containing multiple drugs with defined release profiles. International journal of pharmaceutics, 2015. 494(2): p. 643-650.

125. Lim, S.H., et al., Three-dimensional printing of carbamazepine sustained-release scaffold. Journal of pharmaceutical sciences, 2016. 105(7): p. 2155-2163.

126. Melocchi, A., et al., Hot-melt extruded filaments based on pharmaceutical grade polymers for 3D printing by fused deposition modeling. International journal of pharmaceutics, 2016. 509(1): p. 255-263.

127. Moulton, S.E. and G.G. Wallace, 3-dimensional (3D) fabricated polymer based drug delivery systems. Journal of Controlled Release, 2014. 193: p. 27-34.

128. Sadia, M., et al., Adaptation of pharmaceutical excipients to FDM 3D printing for the fabrication of patient-tailored immediate release tablets. International journal of pharmaceutics, 2016. 513(1): p. 659-668.

129. Pietrzak, K., A. Isreb, and M.A. Alhnan, A flexible-dose dispenser for immediate and extended release 3D printed tablets. European Journal of Pharmaceutics and Biopharmaceutics, 2015. 96: p. 380-387.

130. Goyanes, A., et al., Effect of geometry on drug release from 3D printed tablets. International journal of pharmaceutics, 2015. 494(2): p. 657-663.

131. Goyanes, A., et al., 3D printing of medicines: engineering novel oral devices with unique design and drug release characteristics. Molecular pharmaceutics, 2015. 12(11): p. 4077-4084.

132. Yu, D.-G., et al., A novel fast disintegrating tablet fabricated by three-dimensional printing. Drug development and industrial pharmacy, 2009. 35(12): p. 1530-1536.

133. Yu, D.-G., et al., Novel drug delivery devices for providing linear release profiles fabricated by 3DP. International journal of pharmaceutics, 2009. 370(1): p. 160-166.

134. Wang, C.-C., et al., Development of near zero-order release dosage forms using three-dimensional printing (3-DP™) technology. Drug development and industrial pharmacy, 2006. 32(3): p. 367-376.

135. Huang, W., et al., Levofloxacin implants with predefined microstructure fabricated by three-dimensional printing technique. International journal of pharmaceutics, 2007. 339(1): p. 33-38.

136. Rowe, C., et al., Multimechanism oral dosage forms fabricated by three dimensional printing™. Journal of controlled release, 2000. 66(1): p. 11-17.

137. Hirshfield, L., et al., Dropwise Additive Manufacturing of Pharmaceutical Products for Solvent-Based Dosage Forms. Journal of pharmaceutical sciences, 2014. 103(2): p. 496-506.

138. Daly, R., et al., Inkjet printing for pharmaceutics—a review of research and manufacturing. International journal of pharmaceutics, 2015. 494(2): p. 554-567.
139. Alomari, M., et al., *Personalised dosing: printing a dose of one’s own medicine*. International journal of pharmaceutics, 2015. 494(2): p. 568-577.

140. Tarcha, P.J., et al., *The application of ink-jet technology for the coating and loading of drug-eluting stents*. Annals of biomedical engineering, 2007. 35(10): p. 1791-1799.

141. Gupta, M.K., et al., *3D printed programmable release capsules*. Nano letters, 2015. 15(8): p. 5321-5329.

142. Macdonald, E., et al., *3D printing for the rapid prototyping of structural electronics*. IEEE Access, 2014. 2: p. 234-242.

143. Ota, H., et al., *Application of 3D printing for smart objects with embedded electronic sensors and systems*. Advanced Materials Technologies, 2016. 1(1).

144. Espalin, D., et al., *3D Printing multifunctionality: structures with electronics*. The International Journal of Advanced Manufacturing Technology, 2014. 72(5-8): p. 963-978.

145. Hedges, M. and A.B. Marin. *3D Aerosol Jet® Printing-Adding Electronics Functionality to RP/RM*. in DDMC 2012 conference. 2012.

146. King, B. and M. Renn. *Aerosol Jet direct write printing for mil-aero electronic applications*. in Palo Alto Colloquia, Lockheed Martin. 2009.

147. Hoey, J.M., et al., *A review on aerosol-based direct-write and its applications for microelectronics*. Journal of Nanotechnology, 2012. 2012.

148. Seifert, T., et al., *Aerosol Jet Printing of Nano Particle Based Electrical Chip Interconnects*. Materials Today: Proceedings, 2015. 2(8): p. 4262-4271.

149. Zhao, D., et al., *Conductivity enhancement of aerosol-jet printed electronics by using silver nanoparticles ink with carbon nanotubes*. Microelectronic Engineering, 2012. 96: p. 71-75.

150. Eckstein, R., et al., *Aerosol jet printed top grids for organic optoelectronic devices*. Organic electronics, 2014. 15(9): p. 2135-2140.

151. Rahman, T., et al., *Aerosol based direct-write micro-additive fabrication method for sub-mm 3D metal-dielectric structures*. Journal of Micromechanics and Microengineering, 2015. 25(10): p. 107002.

152. Exner, J., et al., *Tuning of the electrical conductivity of Sr (Ti, Fe) O 3 oxygen sensing films by aerosol co-deposition with Al 2 O 3*. Sensors and Actuators B: Chemical, 2016. 230: p. 427-433.

153. Paulsen, J.A., et al. *Printing conformal electronics on 3D structures with Aerosol Jet technology*. in Future of Instrumentation International Workshop (FIIW), 2012. 2012. IEEE.

154. Yin, Z., et al., *Inkjet printing for flexible electronics: Materials, processes and equipments*. Chinese Science Bulletin, 2010. 55(30): p. 3383-3407.

155. Kamyshny, A., J. Steinke, and S. Magdassi, *Metal-based inkjet inks for printed electronics*. The Open Applied Physics Journal, 2011. 4(1).

156. Mei, J., M.R. Lovell, and M.H. Mickle, *Formulation and processing of novel conductive solution inks in continuous inkjet printing of 3-D electric circuits*. IEEE transactions on electronics packaging manufacturing, 2005. 28(3): p. 265-273.

157. Zhang, W., et al., *Synthesis of Ag/RGO composite as effective conductive ink filler for flexible inkjet printing electronics*. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2016. 490: p. 232-240.

158. Stringer, J., et al., *Integration of additive manufacturing and inkjet printed electronics: a potential route to parts with embedded multifunctionality*. Manufacturing Review, 2016. 3: p. 12.

159. Miettinen, J., et al., *Inkjet printed system-in-package design and manufacturing*. Microelectronics Journal, 2008. 39(12): p. 1740-1750.

160. Willis, K., et al. *Printed optics: 3D printing of embedded optical elements for interactive devices*. in Proceedings of the 25th annual ACM symposium on User interface software and technology. 2012. ACM.

161. Chang, Y.-H., et al., *A facile method for integrating direct-write devices into three-dimensional printed parts*. Smart Materials and Structures, 2015. 24(6): p. 065008.
162. Yang, Y., et al., *Three dimensional printing of high dielectric capacitor using projection based stereolithography method*. Nano Energy, 2016. 22: p. 414-421.

163. Jang, S.H., et al., *3-dimensional circuit device fabrication process using stereolithography and direct writing*. International Journal of Precision Engineering and Manufacturing, 2015. 16(7): p. 1361-1367.

164. Li, J., et al., *Hybrid additive manufacturing of 3D electronic systems*. Journal of Micromechanics and Microengineering, 2016. 26(10): p. 105005.

165. Joe Lopes, A., E. MacDonald, and R.B. Wicker, *Integrating stereolithography and direct print technologies for 3D structural electronics fabrication*. Rapid Prototyping Journal, 2012. 18(2): p. 129-143.

166. Vogeler, F., et al., *An initial study into Aerosol Jet® printed interconnections on extrusion based 3D printed substrates*. Strojniški vestnik-Journal of Mechanical Engineering, 2013. 59(11): p. 689-696.

167. Swensen, J.P., et al., *Printing three-dimensional electrical traces in additive manufactured parts for injection of low melting temperature metals*. Journal of Mechanisms and Robotics, 2015. 7(2): p. 021004.

168. Wu, S.-Y., et al., *3D-printed microelectronics for integrated circuitry and passive wireless sensors*. Microsystems & Nanoengineering, 2015. 1: p. 15013.

169. Aguilera, E., et al. *3D printing of electro mechanical systems*. in Proceedings of the Solid Freeform Fabrication Symposium. 2013.

170. Hoerber, J., et al., *Approaches for additive manufacturing of 3D electronic applications*. Procedia CIRP, 2014. 17: p. 806-811.

171. Folgar, C., et al. *Multifunctional material direct printing for laser sintering systems*. in International solid freeform fabrication symposium. 2013.

172. Siggard, E.J., et al. *Structurally embedded electrical systems using ultrasonic consolidation (UC)*. in Proceedings of the 17th solid freeform fabrication symposium. 2006.

173. Robinson, C.J., et al. *Integration of direct-write (DW) and ultrasonic consolidation (UC) technologies to create advanced structures with embedded electrical circuitry*. in Proceedings of the 17th Solid Freeform Fabrication Symposium. 2006.

174. Li, J., et al., *Exploring the mechanical performance and material structures of integrated electrical circuits within solid state metal additive manufacturing matrices*. 2014.

175. Li, J., et al., *Exploring the mechanical strength of additively manufactured metal structures with embedded electrical materials*. Materials Science and Engineering: A, 2015. 639: p. 474-481.

176. Derakahshani, M., B.E. Allgeier, and T.A. Berfield, *A MEMS-scale vibration energy harvester based on coupled component structure and bi-stable states*. arXiv preprint arXiv:1805.04593, 2018.

177. Fuller, S.B., E.J. Wilhelm, and J.M. Jacobson, *Ink-jet printed nanoparticle microelectromechanical systems*. Journal of Microelectromechanical systems, 2002. 11(1): p. 54-60.