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A Survey of 3D Printing Technologies as Applied to Printed Electronics

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ABSTRACT 3D printing technologies (3DP) leverage the benefits of additive manufacturing across many areas including electronics, food, medicine and optics. These technologies allow varying materials to be precision deposited, forming structures ranging from simple to complex composites such as organs and satellites. One important application for 3DP is printed electronics which is expected to exceed USD10 billion in market value by 2030. However, while considerable work has been reported in areas including inter alia: mechanical, thermal and multiple aspects, there has been less emphasis on the critical electromagnetic (EM) domain. In the EM domain, related work for 3DP encompasses interrelated EM studies of materials, processes and built structures and examines material characteristics including permittivity, permeability, electrical conductivity, which are foundational to 3D printed electronics design and fabrication. This paper presents a comprehensive report of 3DP technologies as applied to EM research & development (R&D) and end applications in order to inspire exploratory work in related areas by providing sufficient breadth for newcomers and depth for experts. The paper contributions include: summarization of the major R&D and applications areas for 3DP, thereby quantifying the prevalence of EM related work; examination of mainstream 3DP technologies applied to EM related R&D and end applications based on their materials, technology highlights and known issues; examination of relevant research which incorporates traditional printing, proprietary methods and composite 3DP methods; and classification of 3DP built EM structures as reported by research teams. Finally, the key challenges and opportunities for future research are identified and discussed.

INDEX TERMS Additive manufacturing, 3D printing, printed electronics, electrical properties.

I. INTRODUCTION

3D printing (3DP) has continued to receive sustained interest with a steady increase in the areas of end application and ongoing research and development work [1]. 3DP can be considered to fall under the umbrella of additive manufacturing processes. Additive manufacturing processes involve the controlled deposition of material in order to build up the desired object [2], [3]. While historically 3DP has played a role in prototyping, recent advances have allowed the technology to be used for producing outputs comparable to manufactured items created using traditional manufacturing methods. Within recent years the areas of application for 3DP have grown to include: electrical, medical, mechanical, social impact, consumer goods and prototyping [4], [5]. One expanding area of 3DP is printed electronics which is forecasted to exceed a market value of USD10 billion by the year 2030 [6], [7]. However, while there has been considerable work in 3DP in the areas of mechanical, thermal and multidisciplinary there has not been comparable emphasis placed on the electromagnetic (EM) domain. EM related work for 3DP encompasses many areas with interrelated studies of materials such as insulative, dielectric, ferromagnetic, conductive etc.; processes and built structures and examines characteristics including permittivity, permeability, conductivity and frequency response which are foundational to 3D printed electronics. This survey was undertaken in order to present the readership with an understanding of the state of the art of 3DP technologies as applied to EM research & development (R&D) and related end applications. The authors believe that an examination of this topic is timely due to recent global events including the advent of the COVID-19 pandemic in December 2019 and the geopolitical shifts which disrupted traditional trade relationships between

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major markets. The ongoing political tensions and fallout from the pandemic continue to reveal the global supply chain uncertainties in many areas including electronic components and assemblies [8], [9]. These events have led to increased interest in the reshoring of electronics manufacturing and related research. As these changes continue to unfold it is important to consider the role that additive manufacturing of electronics will play in the reshaping of these industries and the related research by considering the present state of the art. It is hoped that this work will inspire exploratory work in related areas by providing sufficient breadth for newcomers and depth for experts.

For this survey, publications related to 3DP technologies as applied to EM related R&D and EM end applications were analyzed. An instance of surveyed work was classified as end application if the 3DP technology was used as a tool in undertaking the work. Surveyed work was considered R&D related if it involved the study of the 3DP technology. For the selected published work, the 3DP technologies were identified and discussed. Related non-3DP technologies were also considered in the analysis. The EM structures which were built in the surveyed literature were also identified. The major contributions of this survey include:

- Quantization of the prevalence of EM related research and application work in 3DP.
- Identification of trends in established 3DP technologies as applied to EM related R&D and end applications.
- Identification of trends in non-3DP but related technologies applied to EM including traditional printing, proprietary methods and composite 3DP methods.
- Classification of 3DP built EM structures as reported by research teams.
- Identification of the key challenges and opportunities for future work.

The remainder of this survey is structured as follows. Section 2 will provide an overview of the common 3DP technologies which have been utilize for EM related R&D and EM end applications. Combinations of 3DP technologies, traditional printing methods and proprietary technologies which have also been adapted to EM applications and research will be covered in Section 3. The various EM structures which have been constructed using 3DP methods will be described in Section 4. The survey will conclude with a discussion regarding the challenges facing the utilization of 3DP to EM related applications and the areas of opportunity for future R&D.

The adoption of 3DP processes to EM related R&D and EM end applications presents unique opportunities. However, the adoption of suitable 3DP processes faces many challenges including the capabilities of existing processes (accuracy, speed, repeatability, resolution) and materials (lack of characterization of electrical properties, consistency of reconstituted materials) [6]. These challenges can present opportunities for renewed cycles of research.

II. ESTABLISHED 3DP TECHNOLOGIES

3DP technologies encompass various methods which incrementally build the desired object based on its CAD model [2]. Some of the existing 3DP technologies used with EM applications and research are well established. Others are restricted to specific research groups (for example, as evident by the patent filings) or are in the infancy stage and thus confined to experimental applications [10]. The various techniques can be characterized based on the materials that can be utilized, the process speed, accuracy and proprietary vs open source [11], [12]. In an effort to bring consistency to the terminology used to describe the 3DP technologies as well as to manage the issue of trademarks, the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have produced various standards covering different 3DP topics [13], [14]. The ISO/ASTM 52900:2021 Additive manufacturing - General principles - Fundamentals and vocabulary defines seven categories of 3DP technologies [15]:

- Vat photopolymerization
- Material jetting
- Material extrusion
- Binder jetting
- Powder bed fusion
- Directed energy deposition
- Sheet lamination

Despite these standardization efforts, there continues to be a broad mix of naming conventions utilized in the reported literature. For example, there continues to be prolific use of the term Fused Deposition Modeling (FDM) which is a registered trademark of the company Stratasys as compared to the open term Fused Filament Fabrication (FFF) [13], [14], [16]. For this survey, the ISO/ASTM 52900:2021 standard was considered when reviewing the literature of the established 3DP technologies as applied to EM related R&D and end applications. Based on the literature, the following six technologies were identified:

- FFF
- Stereolithography
- Material extrusion
- Material jetting
- Powder bed fusion
- Binder jetting

The selection of the categories was influenced by several factors. The FFF technology is considered under the ISO/ASTM standard to be part of material extrusion processes [15]. However, due to the prevalence of FFF technology in the reported EM related work, FFF was considered separately for this survey. The ISO/ASTM standard considers the jetting of photosensitive material under material jetting, other processes which involve light-activated curing are considered under vat photopolymerization [15]. For this survey material jetting of photopolymers and vat photopolymerization processes are captured under stereolithography due to the similarities of the EM related properties and other related factors [17].

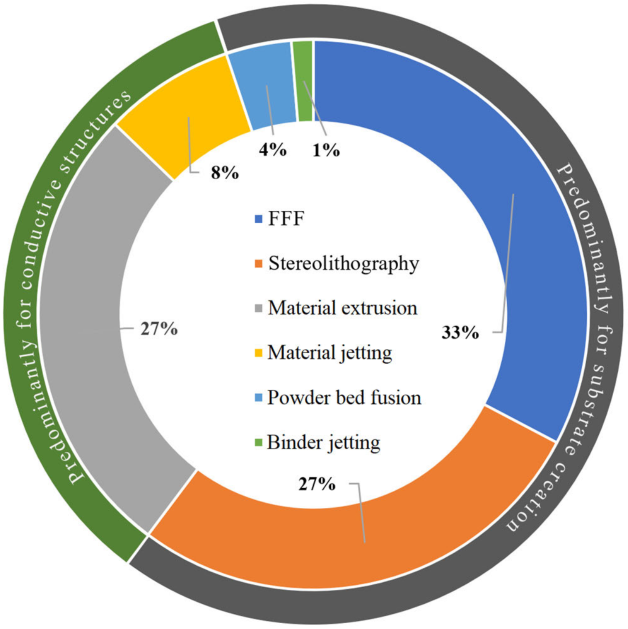

FIGURE 1. Distribution of the utilization of the established 3DP technologies for EM related applications and research.

Figure 1 illustrates the distribution of the utilization of the established 3DP technologies for EM related applications and research based on the published literature reviewed for this survey. From the published work it was noted that certain 3DP methods were predominantly utilized for substrate creation of electrical and electronics structures. These processes included: FFF, stereolithography, powder bed fusion and binder jetting. Other processes were found to be used predominantly for conductive structures. These processes included: material extrusion and material jetting. Of all the established methods reported, FFF, stereolithography and material extrusion represented the most utilized methods of 3DP adopted for EM applications and research.

The authors also wish to make mention of the family of substrate-based manufacturing processes known as roll-to-roll (R2R). In its simplest form, R2R manufacturing techniques involve the continuous processing of flexible substrate materials which are transferred between two moving rolls [18]. R2R processes were not considered in this survey since these processes are generally aimed at repetitive, high volume, large area applications compared to the highly reconfigurable and scalable nature of the traditional 3DP methods. The interested reader may obtain more information from several published reviews and resources on R2R technologies and applications [19]–[21].

In the following subsections the established methods of 3D printing will be described including:

- General overview of the technology
- Materials
- Key technology highlights
- Known issues

The key information related to the established 3DP processes is summarized in Table 1.

A. FUSED FILAMENT FABRICATION (FFF)

1) OVERVIEW

FFF printing is currently one of the lowest costing 3DP processes with a large range of printers and materials both open source as well as proprietary [22], [23]. The proliferation of printers is due in part to the expiration of key patents surrounding FFF technology [24], [25]. The FFF machines are also relatively inexpensive and simple to operate compared to other processes and the printing process can be undertaken in air at room temperature [23].

The FFF process starts with a 3D model file which is either drawn OR created by scanning an object [26]. The model is then sliced into a series of layers and support structures are added. The FFF printing process works by melting the filament into a semiliquid state using a heating nozzle and extruding the material in layers. As the printing progresses, the thermal energy of the melted filament is partially imparted to the previous layer allowing for bonding. When each layer is completed the print bed is lowered and the next layer is added [12], [22], [27].

2) MATERIALS & APPLICATIONS

The majority of FFF materials are thermoplastics which are in the form of a filament [16], [22]. These materials tend to have low processing temperatures with two of the most popular materials being Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA) with PLA having a lower processing temperature and being less toxic [22], [28]. Considerable research has been conducted to study the mechanical properties of the materials and the printed structures with specific focus also placed on the thermal properties and how they impact warping [29].

In addition to the materials and part cooling, print quality is affected by several factors including nozzle diameter (which affects layer thickness) print orientation, raster width, raster angle, air gap, material feed rate and print speed [11], [22], [23], [30]. The print quality can also be affected by the difficulty to remove the support material. FFF printed parts are also known to be weakest along their print lines and this is where breaks and fractures are most likely to take place [31]. It is important to note that FFF does not provide superior resolution and surface finish when compared to other printing methods.

A key aspect of the FFF technology is the emergence of equipment which can process multimaterials and the growing availability of material composites. Many FFF printers currently offer the ability to print with multiple extrusion nozzles which can allow printed parts to be built from several materials in one build cycle [22]. However, in cases where the machine switches between the different nozzles, the cooling and heating cycles can lead to nozzle clogging. In the case of material composites, many FFF filament materials can be easily mixed with other materials to form composites [22]. One example composite combines ceramics and polymer to improve physical and mechanical properties [44]. Ceramics

TABLE 1. Summarization of key points for established methods of 3D printing related to electrical and electromagnetic applications and research.

Method	Materials	Process overview	Proprietary/ open source	Advantages	Disadvantages	*Performance Parameters
FFF	Thermoplastics	Extrusion and dispensing	Wide variety of open source and proprietary technologies	Simple process, greatest range of materials, filler options allow for conductive and other properties. Multimaterial capable	Resolution restricted by nozzle diameter. Anisotropic properties along print lines. Conductive structures show high resistance.	OC Low [32] EC 0.5k – 400k [33], [34] PS 50-100mm/s [35] A ±0.1 – 0.4mm [36] C (3-6)e-2S/cm [37]-[39]
Material jetting	Organic/inorganic solutions/ suspensions	Drop on demand and evaporation/ post treatment	Few open source, mostly proprietary	Variety of insulative and conductive inks. Multimaterial capable	Inaccuracies due to stray drops. Post processing often required (sintering) to improve material properties such as conductivity.	OC Low [33] EC 8k – 600k [33] PS 500mm/s [40] A 0.02 – 0.5mm [41] C 3.15e5S/cm [40]
Binder jetting	Variety of powdered materials	Binder adhesive selectively sprayed to bind powder	Few open source, mostly proprietary systems	Wide variety of materials, multimaterial capable (powder mix)	Risk of contamination, inaccuracies due to stray binder drops. Poor mechanical strength.	OC Medium [42] EC 5k – 1.8M [33] PS 160-3500cm3/h [42] A 0.2mm [43], [44] C 0.47 x 10^7 S/m [45]
Material extrusion	Wide variety of solutions and pastes	Syringe dispensing followed by curing	Wide variety of open source and some proprietary technologies	Wide variety of materials including conductive options. Multimaterial capable	Post processing required (sintering) to improve conductivity, mechanical strength.	OC Low EC 0.5k – 400k [33] PS 4-150mm/s [46], [47] A ±0.1 – 0.4mm [36] C 6-30S/cm [48]
Stereolithography						
Poly jetting	Photocurable resins	Multiple jetting heads and UV curing	All platforms are proprietary	Good resolution, multimaterial compatible	Limited material options,	OC Medium [32] EC 20k – 600k [33] PS 2-60cm3/h [35] A ±0.05 – 0.5mm [36] C 1e-1S/cm [49]
Vat polymerization		Laser curing of bulk material		Good resolution	Limited material options, risk of contamination	OC Medium [32] EC 0.5k – 800k [33] PS 1-6cm3/h [35] A ±0.05 – 0.5mm [36] C 5e-2S/cm [50]
Digital light projection		Light projection curing of bulk material		Good resolution	Limited material options, risk of contamination	OC Medium EC 0.5k – 800k [33] PS 1-12cm3/h [35] A ±0.05 – 0.5mm [36] C 2.7e-4S/cm [51]
Powder bed fusion						
Electron beam melting	Polyamides and metal powders	Material melted using a focused beam of electrons	Few open source, mostly proprietary systems	High strength, wide material options, multimaterial capable (powder mix),	Surface finish is rough and requires post machining, risk of contamination	OC High [42] EC 200k – 5.0M [33] PS 55/80cm3/h [52] A ±0.2 – 0.5mm [52] C 5.5e5S/cm [53]
Selective laser sintering/melting		Material sintered/melted using optic laser	Proprietary	High strength, wide material options, multimaterial capable (powder mix),	Surface finish for sintering is rough and requires post machining, risk of contamination,	OC High [42] EC 20k – 2.0M [33] PS 5-120cm3/h [54] A ±0.2 – 0.5mm [36] C 1.54e5S/cm [45]

*OC – Operating Cost; EC – Equipment Cost; PS – Printing Speed; A – Accuracy; C - Conductivity such as BaTiO3 and TiO2 have also been used to alter the dielectric properties of composite material [22], [27]. Other applications involve conductive materials which contain oriented reinforced fibers [55]. Composites have been developed which contain a host of particles including metal, wood, glass and carbon [26], [56]. In other applications, composites have been used to help manage the warping that occurs during cooling (e.g. using iron particles) [29]. Finally, researchers have also attempted to use the affinity of the thermoplastics/ability to absorb liquids to impregnate the printed part with electrolytes [57].

An area of keen interest for FFF printing applied to EM applications and research is the processing of metals. Printing of metals is always a challenge because of the high temperatures required. One approach involves the use of conductive and ferromagnetic polymer composites which are loaded with metal nanoparticles [58]–[60]. One commercial solution which has been developed for metal printing using metal loaded filament is produced by Markforged Ltd. Another approach is the use of conductive inks and pastes however the challenge is that many conductive inks and paste require post treatment with sintering at high temperatures which are well above the processing temperatures of the thermoplastics. Special plastics can be used but they are either expensive and/or require much higher processing temperatures [61]–[63]. There currently are several high-temperature thermoplastics which can be processed using FFF, these include: polysulfone (PSU), polyphenylsulfone (PPSU), polyphenylene sulfide (PPS) polyether imide (PEI), polyether ketone (PEK), polyether ketone (PEKK), and polyether ether ketone (PEEK) [62], [64]. Because of the high processing demands associated with these materials there are fewer FFF printers capable of working with the materials and significant equipment costs (FFF printer cost estimated at >USD50k) [65].

3) PROCESS ISSUES

In adapting FFF printing to producing electrical structures one can consider two areas which would affect the EM properties of the printed object, the first being the materials and the second being the printing process itself. From the electromagnetic research angle, there is still a large gap in the characterization of the EM properties (such as dielectric constant and loss tangent) of FFF printed parts and materials owing to the on-going development of processes and the materials [23].

At the printing process level there are several factors which impact the application of FFF to electronic structures. These factors include the surface finish of printed part, the resolution of the printing process, warping of the printed part during cooling and the impact of nozzle and material temperatures on electronic components [23], [29]. The rough surface finish of the printed part negatively affects the ability to apply pastes and inks (both conductive and insulative) [23], [63]. The uneven surface presents a longer path for current flow and thus greater resistance [23]. This effect is amplified for higher frequencies where signals are predominantly in the outer skin of the conductor [66]. The print lines on the rough surface are also known to act as trenches along which the inks and pastes would bleed leading to potential shorts [63]. The rough surface finish is caused by many factors including less than optimal infill and marks left from the removal of rafts (rafts are low density, easy to remove supports which are printed below parts). To improve surface finish, methods such as chemical misting, baking, CNC milling and sanding have been proposed [67]. In the case of CNC milling, the process does not fill gaps and creates waste [23]. In the case of chemical misting (an example of this is the use of acetone with ABS [68]), the processes are difficult to control and can result in excessive melting and deformation [23]. The process of post baking the printed part involved heating up to the material's glass-transition temperature however this process causes shrinkage [67]. Milling of the printed substrate has also been considered in order to create channels for the deposition of the conductive inks and pastes. These channels are considered necessary in order to prevent the conductive pattern from being damaged as the subsequent layer of thermoplastic is added to the 3D structure [44]. Another process level issue is the poor resolution of FFF which limits the ability to print fine electronic features (e.g. fine pitch pins), limits the ability for the insertion of electronic components and also results in gaps in the printed structure [23]. Gaps in the printed structure would cause porosity which can lead to the spreading of conductive inks and pastes between electrical lines resulting in electrical shorts [69]. To compensate for the resolution issues encountered with component insertion, pockets are printed into the substrate and then milled to the required tolerance. Finally, the issue of warping is a significant problem which causes twisting of the substrate during cooling which also affects the conductive structures and impacts the performance of the electronic devices [70].

B. MATERIAL JETTING (MJT)

1) OVERVIEW

The process of material jetting (MJT) 3DP is a nonimpact printing method which involves the production of droplets of material particles which are deposited so that they bond to build a desired object [44]. There are several technologies for the production of droplets including thermal bubble, piezoelectric, diaphragm, and electric field [44]. The MJT printing process also has the advantage of being operated at room temperature without any special printing environment however the post processing of the ink material is demanding [71]. The post treatment processes may involve heating and or sintering to reconstitute the printed ink. For conductive inks the post processing may include thermal, photonic or chemical sintering [71].

2) MATERIALS

MJT 3DP is a relatively cheap process due to the availability and compact nature of the printing equipment and the one step nature of the process [72], [73]. However, the materials used for MJT can be a significant cost of the process in particular conductive inks which feature metal nanoparticles such as silver and gold [73]. The process is also limited in terms of print speed owing to the ink droplet sizes. To address the speed limitations manufacturers have utilized multihead and multijetting techniques to improve print times [74], [75]. Another method adopted to increase printing speeds involves the use of a rotating build plate with an array or print heads to achieve continuous printing without pauses [76].

A variety of materials can be deposited using MJT 3DP [77]. MJT 3DP has been used to produce conductive structures, dielectrics, insulators and photoactive materials [44], [78]–[80]. A significant challenge with MJT 3DP inks is the fact that the process is best suited to less viscous inks [75], [81]. Because of the need to consider material viscosity, inks can only be loaded with conductive and other particles to a limit before being incompatible with the printing process [58], [82].

3) TECHNOLOGY HIGHLIGHTS

Application wise, MJT is most frequently used to build electrical structures with metal nanoparticle [74]. Researchers have also investigated metal-organic decompositions and aqueous conductive solutions as alternatives to the nanoparticle inks [77], [83]. Nanoparticle inks require post processing (evaporation of solvents and/or sintering) in order to be able to fuse and form solid structures. The longer the sintering process the greater the improvement in conductivity [83]. Nanoparticle ink printer have been produced for metals and ceramics by companies such as XJet [84]. Commercial units (Océ®technology) have also been developed which are capable of dispensing liquid metal droplets from a heated print head [77]. Other commercial systems (Vader Systems) melt solid metal wire to create a molten metal reservoir where droplets are ejected using an EM pulse [85].

4) PROCESS ISSUES

The application of MJT 3DP to the creation of electrical structures is impacted by two main factors, the EM properties of the materials and quality of the printing process. At the material level, several MJT printer systems feature multiple nozzles or allow for the mixing of materials prior to jetting thus allowing for the printing of multimaterials [44]. The printing of multimaterials has in turn allowed for the creation of structures which have varying EM properties (for e.g. dielectric constant).

In the area of print quality there are several factors at play which include resolution, accuracy and compatibility. A key factor which impacts MJT 3DP is the compatibility between the MJT ink and the underlying substrate [83]. However, MJT printing has been shown to be possible with a host of substrates including plastic, glass, ceramics, silicon, flexible membranes, gels, thin films and paper products [77]. The resolution of the MJT 3D printed object is very good being of the micron scale $\approx 0.06 - 0.15\mu$ in size [78], [86]. However, the possibility of stray droplets depositing within the structure leading to open or short circuits is of concern. The print quality is considered comparable to traditional photolithography processes [71], [75].

C. BINDER JETTING (BJT)

1) OVERVIEW

Binder jet technology (BJT) was first introduced in 1993 out of work at the Massachusetts Institute of Technology (MIT) [87]. The BJT process involves the selective binding of powder particles. The first step in the creation of a component is the laying of a thin layer of powered material. Onto this layer a pattern of binder adhesive is jetted and the build platform is lowered to allow for the depositing of the next powder layer which is again patterned with the binder adhesive. The process repeats until the 3D component is complete. The complete object is finally pulled out of the bed of unbound powder [22]. There are many factors which affect the quality of the printed component these include the size, shape and consistency of the powdered material and the compatibility between the binder adhesive and powder [88].

2) MATERIALS

There are several advantages to BJT 3DP, these include the ability to operate the process at room temperature, the broad array of materials which can be used in this process and the relatively easy removal of support materials [22]. Based on the basic operation of powder binding any material which can be milled into powder form can be utilized using the BJT process with a suitable binding adhesive. Materials can also be of varying particulate sizes and a variety of material types can be combined to realize multimaterials as well as composite structures [2]. An interesting application of the multimaterial approach is the inclusion of sacrificial powders which can be purged out of the printed structure to allow for varying levels of porosity [44]. Common process materials include gypsum, plastics and silica and a common adhesive is cyanoacrylate. Various manufacturers also allow for the dispensing of colored dyes to allow for printing in color [23], [87]. Finally, as the object is built, the unbound powder acts as the support material. Therefore, no explicit support structures are required resulting in no surface scaring due to detaching support structures. Recent renewed work in the area of BJT which would be applicable to EM structures would be printing of metal parts [87]. Commercial BJT printers are available which are capable of processing ceramics (ExOne, Voxeljet) and metals (ExOne).

3) PROCESS ISSUES

There are also many disadvantages to BJT 3DP, these include significantly higher equipment complexity and costs, poor resolution and accuracy, safety hazards of working with the powered materials, significant contamination risk, structurally weak printed components, components which are porous with rough surface finish and finally the power/adhesive structures vary significantly in their characteristics compared to the stock materials (e.g. bound metal powders and their electrical conductivity; bound plastics and their resultant permittivity) [87]. The equipment utilized for BJT printing is not as readily available as more prolific processes such as FFF. In addition, the BJT process is of a higher complexity requiring an enclosed environment to reduce contamination, safe handling and storage of materials and the safe cleaning and post processing of the printed part [2].

The resolution of BJT is restricted by the powder layer thickness and binder jetting resolution can be as small as 300 x 300 DPI or approximately three particles thick [87], [88]. Achieving an even and compact layer of material is difficult. The binder jetting also affects the possible resolution based on the powder/adhesive interaction as the adhesive impacts the powder surface and spreads through capillary action. The finer powdered materials can pose a significant health risk with the powder removal process usually required to be conducted in an enclosed chamber. The risk of material contamination is also very high during component removal, material handling and storage between prints [22]. BJT components are also usually weak with a rough surface finish. Post processing is often utilized to improve the surface finish such as applying coatings. Processing of complex or internal structures is particularly challenging. To improve strength, the printed component may be sintered or infiltrated [87], [88]. Sintering can allow the particles to melt and bind thus achieving properties similar to the stock materials. Sintering can also allow for the removal of the binding adhesive through vaporization. Thus, the sintering approach can allow for the binding of metal particles in electrical structures. However, sintering does present several issues the most significant of which is the modification of the printed component's dimensions which may also result in warping and fracturing. Infiltration is another method used to improve structural strength of the printed component through the use of penetrating liquids. An interesting application of the infiltration process is the use of conductive inks or low melting metals to infiltrate the printed structure to improve the electrical properties [44]. However, infiltration faces difficulties in achieving penetration of the infiltrant into the depths of the printed structure resulting in an uneven effect.

D. MATERIAL EXTRUSION (ME)

1) OVERVIEW

Material extrusion (ME) methods can be categorized into a broad set of 3DP technologies including liquid deposition, micro dispensing [23], direct writing [22], and robocasting [89]. The FFF 3DP technology also falls under the family of ME processes [90]. For this survey paper, the area of FFF 3DP as relates to EM research and application has been previously discussed in a separate, standalone section due to the significant prevalence of FFF in the reported literature. There are also many novel and/or proprietary extrusion processes such as Aerosol printing. These novel and proprietary processes are introduced in the later sections of this survey paper. ME is one of the most utilized methods for printing conductive materials for EM related research and applications [91]. In its simplest form ME involves the dispensing of material from a pressurized syringe which is mounted onto a moving gantry system which controls the pattern of dispensed material [90]. After each layer is constructed the build platform is either lowered or the printing head indexed and the next layer added. In some instances, the gantry system can allow for motion in more than two axes thus allowing for more build freedom. The build freedom allows ME to be easily adapted to conformal printing which makes it suited for printing flexible, compact and/or encapsulated devices [25]. The materials are most often in the form of a paste, solutions or hydrogels. The initial printed structure is termed 'green' until it is cured. Curing can be achieved by mixing a curing agent into the material prior to printing or through the use of a post process such as heating or UV light [22], [89], [90].

2) TECHNOLOGY HIGHLIGHTS

One benefit of ME is the relatively low cost and availability of the equipment used and the simplicity of the printing process. Another key advantage for ME is the low temperature of extrusion of the material which allows temperature sensitive materials to be processed [28]. While a wide variety of materials can be used with ME, in some instances the synthesis and storage of the materials presents a significant challenge. The ME process is able to print a broad array of materials through the formulation of pastes and solutions which can be dispensed. Through improvements in the dispensing mechanism ME techniques can now support materials with very high viscosities (i.e. high particle loading) and widely varying compositions [92].

3) MATERIALS

Materials which have been used for ME include conductive, resistive, dielectric, ceramics, ferrite, viscoelastic and adhesive pastes [90], [93], [94]. Examples of conductive materials include silver and zinc nanoparticle loaded inks [25], [89], [95]. ME is also one of the simplest and lowest costing methods for multimaterial printing [96], [97]. Because of nature of the materials used for ME it is very simple to combine different materials in paste and solution formulations. Examples of multimaterials included polymer paste and fiber combinations [22], composites of Multi-walled carbon nanotubes (MWCNT) and PLA paste and magnetic responsive materials which are manipulated using an EM field [98]. Components can also be built which are graded OR are composed of composite materials [44]. The ease of processing multimaterials also means that complex electronic structures can be built with capacitive, magnetic and resistive properties [96].

4) PROCESS ISSUES

There are several factors which contribute to the quality of the ME process these include process resolution, substrate compatibility, material formulation and post processing. Process resolution is impacted by the extrusion material, substrate and dispensing nozzle diameter [90]. Many printer systems have been adapted to use micro dispensing techniques in order to improve resolution and produce fine details. Substrate compatibility is a key issue as relates to substrate roughness which impacts the accuracy and adhesion of the printed pattern. Compatibility is also relevant to the interaction between the printed material and the substrate for example minimizing bleeding and spreading which can result in bridging and shorts in printed electrical structures [23]. Extrusion material formulation affects print quality as relates to material rheological properties, useful working life, shape retention and material safety. Considerable work has been done by manufacturers to improve the accuracy and speed of the printing process by improving the rheological properties, especially printing start and stop at the nozzle [23], [81], [91], [99]. The useful working life can also have a significant impact on quality and consistency. For material paste and solution formulations which use solvents or curing agents with a short working life, it is possible for the material in the syringe to become increasingly viscous as the printing progresses resulting in print quality deteriorating over time. Shape retention affects the ability to print complex structures and the materials ability to support itself vs. the need for sacrificial support structures [22]. Finally, the use of various solvents and additives to achieve desirable printer material characteristics can result in hazardous formulations which are challenging to safely process [100]. The remaining area which presents a challenge for ME is the curing stage of the process. The most common curing steps either involve removal of a solvent and/or heating. Both processes can result in porous components which are structurally weak and exhibit poor characteristics such as low conductivity. In the case of heating, elevated process temperatures which result in material melting and bonding can improve strength and other characteristics but this comes at the cost of component deformation and/or shrinkage [89].

E. STEREOLITHOGRAPHY (SLA)

1) OVERVIEW

The stereolithographic printing method (SLA) encompasses several processes which involve selectively irradiating photo-curable polymers with a UV light source in order to build the desired 3D printed structure [2]. Three of the common SLA printing processes are poly-jetting, vat polymerization and digital light projection (DLP). The ISO/ASTM 52900:2021 standard considers the jetting of photosensitive material under material jetting [15]. For the purpose of this survey poly-jetting is considered under SLA due to the similarities of the EM and material related properties and issues compared to the other SLA processes [17]. SLA printing processes are ranked second after FFF in terms of utilization for EM related 3DP applications [23]. SLA is one of the earliest techniques conceived for 3DP and as such its methods are well understood [101]. SLA printing processes also provide very high resolution, surface finish and printed part transparency [23], [31]. The technique is also able to produce structures which do not possess air voids [102]. The printing technique is also considered to be one of the more expensive processes as relates to the equipment and the materials used.

2) MATERIALS

The materials utilized for SLA printing are often specific monomers or oligomers which respond to UV light exposure. There are a variety of photo-curable resins which include polyethylene like materials, ABS like materials, polypropylene like materials and translucent materials [101], [103]. Another important group of SLA materials is multimaterials. Many multimaterials involve the addition of particles including ceramics and ferromagnetic materials or the use of separate reservoirs of photopolymers [44], [104], [105]. There are several challenges associated with these materials which include their toxic nature and poor weathering ability. On the issue of toxicity, a concern is the presence of residual material after washing and curing which would limit the potential end applications of the printing technique (e.g. medical, food). Regarding the problem of weathering, SLA materials have demonstrated poor mechanical strength and dimensional stability due to the impact of heat and sunlight [31], [101], [103].

For the application of SLA printing to electrical structures, photopolymer materials loaded with high dielectric particles have been used to build capacitive structures [44]. The further application of SLA printing to electrical structures is limited by the useful working life of the printed structures and the lack of data on the electromagnetic properties of many photopolymer materials and multimaterials [103]. SLA materials are also known to have greater loss for microwave frequencies (when compared to materials for other 3DP processes such as FFF) and attempts have been made to introduce fillers to compensate for the lossy materials [106], [107]. Silica particles have also been introduced in some instances to improve structural strength.

a: SLA: VAT POLYMERISATION

Vat polymerization is one of the earliest forms of SLA printing. This system involves the use of a reservoir of photocurable polymer material which is selectively cured using a guided light source to build the 3D printed structure. The photocurable polymer is applied and cured in layers until the entire 3D printed structure is constructed. After printing, the 3D printed structure is rinsed and cured further [101], [103]. Additional curing would involve bathing the printed structure in UV light to further solidify [108]. The materials used for vat polymerization are the standard monomers, oligomers and multimaterials used for SLA. To improve the resolution of the printing process the concept of micro-stereolithography was created. The process improvement is achieved by more precise control of the light source and greater control of the polymer layer dimensions. The print quality is affected by the power of the light source (laser), scan speed and duration of exposure [22], [101]. To assist the curing process photo initiators and UV absorbers can be added to the photo polymers.

b: SLA: DIGITAL LIGHT PROJECTION (DLP)

The digital light projection (DLP) process involves the deposition of a layer of photo curable resin followed by the selective curing of the entire layer using a projected light source [22]. The process is repeated to build the 3D printed structure. The DLP 3DP process is the same as vat polymerization except for the method of UV light exposure. A major advantage of the DLP process is the lack of need for X-Y translation of the light source and/or polymer bed. This results in greatly improved printing speeds as well as improved structural strength due to the curing of each build layer in one step [103]. The lack of a moving light source also reduces the mechanical complexity of the printing equipment [109]. The selective light exposure of the entire polymer resin layer is achieved using methods such as a digital micromirror device (DMD) or using a liquid crystal display (LCD) pattern generator [110]. Similar to vat polymerization, methods are used to precisely control the UV light source in order to improve the resolution and accuracy of DLP printing. Digital light projection (DLP) printing also suffers from the same material limitations and challenges faced by vat polymerization. In the area of electrical structures, researchers have reported the application of DLP for the embedding of electronics [109]. Some researchers have reported on the printing of porous structures using DLP which were impregnated post process with metal nano particles in order to make the structures conductive [111]. Materials have also been reported which involve the use of high dielectric particles such as silver decorated lead zirconate titanate (PZT) [112] and ferromagnetic materials to create graded magnetically responsive structures [105]. The use of DLP with photo curable polymers doped with suitable particles has been shown to be applicable for constructing printed circuit boards, producing high-k gate dielectrics and in the embedding of passive components. Currently, one of the most common platforms used for the research of DLP printing is the Texas Instruments DLP chipsets [101].

c: E.3) SLA: POLY-JETTING

The poly-jetting printing process works by jetting photo polymer materials using multiple jetting heads onto a substrate. The printer heads are similar to those used in a material jetting printer and the jetted material is cured using directed UV light [101], [113]. There are a variety of materials used for poly-jet printing which include elastomeric, translucent and opaque. The materials used in the poly-jet printing process have similar requirements to material jetting printing as relates to their need for a sufficiently low viscosity in order to be compatible with the printing heads [23]. Therefore, there is a limit to the ability to add fillers to the photo polymer resins in order to create multimaterials. Also, the particles would affect the translucence of the inks which would impact the curing process [25]. These factors serve to limit the range of possible materials and thus reduce the possible end applications of the printed structures. Multimaterials can also be processed by poly-jetting using techniques which operate separate printing heads for different materials and also methods which blend the material to different concentrations prior to printing. On the issue of quality, the resolution of poly-jetting techniques depends heavily on the ability to accurately and rapidly cure the jetted photopolymer materials [23]. Techniques which have an appreciable gap between jetting and curing can suffer from slumping of the printed structures. The jetting process is also one of the slowest SLA printing methods with manufacturers using multiple printing heads to improve process throughput [44]. Finally, the poly-jetting process is restricted in terms of the complexity of the structures that can be printed with dissolvable support materials being used in some processes to allow for the printing of more complex structures [114].

F. POWDER BED FUSION (PBF)

1) OVERVIEW

Powder bed fusion (PDF) encompasses the group of 3DP processes which involve the selective melting or sintering of powdered material to build the 3D printed structure. The PBF processes are differentiated based on the melting/sintering technique which includes selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM) [115]. There are many challenges with the PBF process which makes it an expensive, complicated and potentially hazardous process. The process requires a high-powered heating source and a build chamber that is either a vacuum or contains an inert gas to prevent oxidation of the materials during processing. The printed structures require controlled cooling to prevent deformation and/or fracture and considerable post processing is required to improve the surface finish of the printed structure [116]. PBF is able to process a variety of materials which can be remelted, these include metals, ceramics and polymers. The process is particularly popular for the processing of metals which require high temperatures [115]. The benefit of metal printing using PBF processes is the elimination of the need for additional metallization processes [117]. Metal materials which can be processed include nickel, iron, stainless steel and titanium [103], [115]. The process can also accommodate multimaterials by mixing the various powdered components. Graded printed structures can also be created by using multiple chambers with different material powders which are deposited to form different layers [44].

a: PBF: SELECTIVE LASER SINTERING (SLS)

The selective laser sintering (SLS) process involves the fusing of powered particles using a high-powered laser which follows a guided path which is produced by the control software [2]. The process works by depositing a layer of powered material and selectively sintering powdered particles using the guided laser. Once the layer is completed another

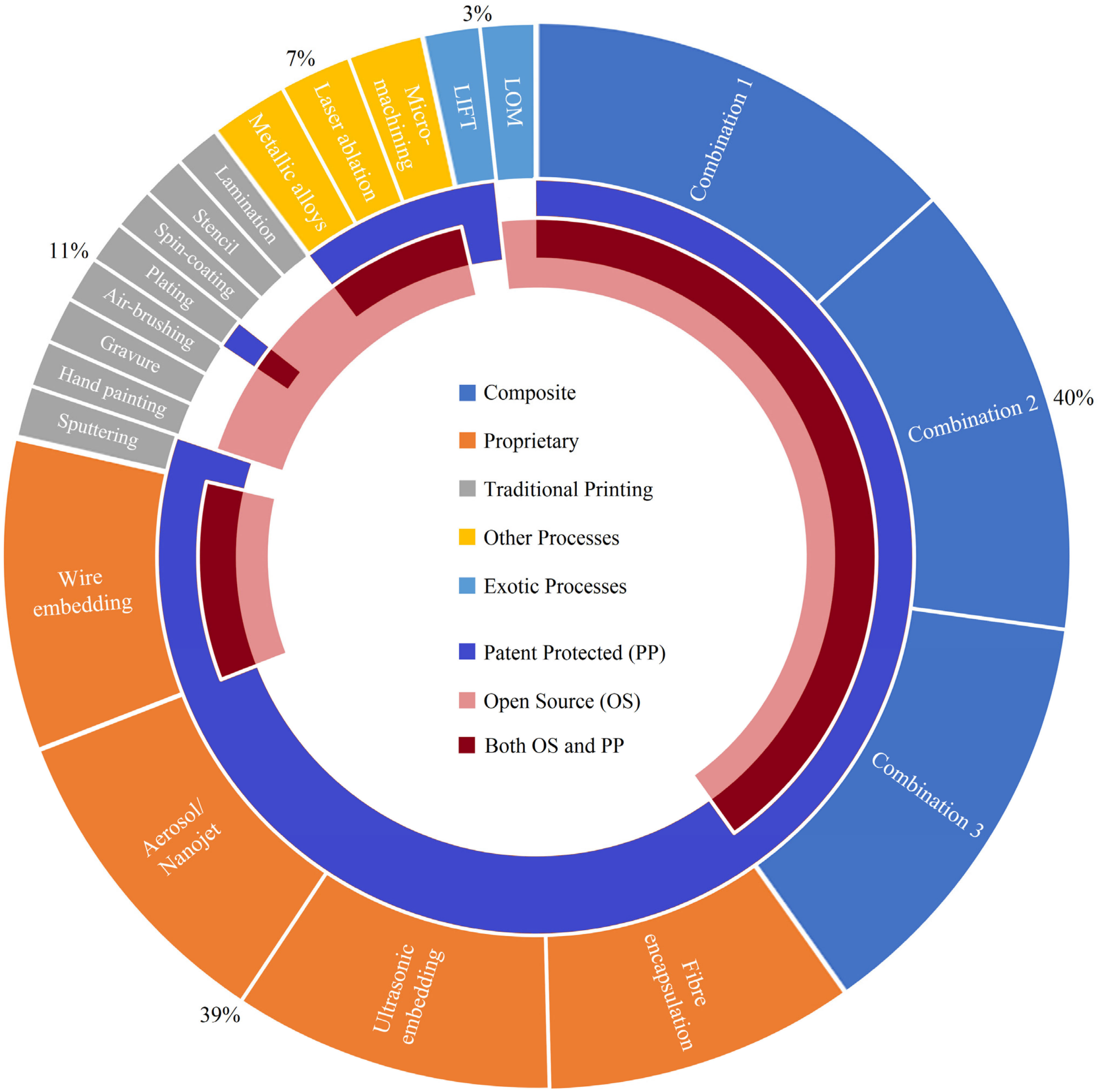

FIGURE 2. Distribution of the patent protection status and utilization of novel 3DP technologies applied to EM related applications and research.

layer is added and the steps repeated. The quality of the printed part is affected by the laser power, scanning resolution and speed and the consistency and size of the powdered materials. In particular, the particle interactions during laser sintering/melting, which may involve clustering and amalgamation, have limited the possible materials. For polymers, polycaprolactone (PCL), polyamide (PA), polyaryletherketone (PEEK) and poly-L-lactide (PLLA) are some materials which are currently used [22], [115]. 3D printed structures produced using SLS demonstrate high surface roughness and poor dimensional accuracy compared to other 3DP technologies [115].

b: PBF: ELECTRON BEAM MELTING (EBM)

Electron beam melting (EBM) utilizes the same process steps as SLS printing but the key difference is that the energy source used for melting the materials is a powerful electron beam. The EBM process is most often used with the processing of metals since it involves very high temperatures and produces high density structures with low internal defects and little fatigue and residual stress. Like all SLS processes EBM is complicated and the process and materials are expensive. The materials used with EBM must be electrically conductive. There is also considerable post processing involved to improve the surface finish but less so than for SLS [115].

III. NOVEL 3DP TECHNOLOGIES

In examining the literature related to 3DP technologies as applied to EM related research and application several specific niche and/or proprietary 3DP technologies were prevalent. There were also several traditional manufacturing technologies which were frequently cited in combination with 3DP methods. In this section we have specifically treated with these technologies. For example, there are several 3DP technologies which utilize specific methods which have been secured as proprietary and are available as commercial solutions. Other methods and technologies which have been adopted involve the use of traditional methods of printing. There were also many reports in the literature of instances where traditional manufacturing methods are adopted in conjunction with 3DP. In some instances, the processes used are very specialized and applied to limited/specific applications. Finally, in order to leverage the advantages provided by the different 3DP technologies many methods/solutions combine several technologies into one system that is used to build the electrical structures. In this section the novel approaches to 3DP applied to EM applications and research will be considered under five areas:

- Proprietary
- Traditional techniques
- Exotic
- Other
- Composite techniques

The five areas and the various processes are detailed in Figure 2 along with the percentage utilization of the various categories as applied to EM applications and research as reported in the literature. Also illustrated is the status of the technologies as either open source, protected or both.

The percentage utilization identifies the proprietary and composite techniques as being the most utilized methods. The dominance of the two areas highlights the emphasis on workable techniques for EM applications and research as well as the push for commercialization of the technologies. The 11% utilization of traditional printing processes and manufacturing processes shows the value of using these well-established methods in conjunction with the 3DP techniques. The remaining subsections will examine each of the five major areas.

A. PROPRIETARY (PRO)

From the review of the literature, several highly prevalent 3DP techniques which are registered specifically as proprietary technologies were identified. These technologies have been used extensively for the creation of electrical structures and are highlighted in this section. These techniques include Aerosol printing, fiber encapsulation and wire embedding (ultrasonic embedding, joule heating). The key information related to the proprietary methods is summarized in Table 2.

1) AEROSOL

The Aerosol process has been patented by Optomec®a comparative system has also been offered by Integrated Deposition Solutions under the name Nanojet [118]. Both systems function under the same principles and involve the deposition of an aerodynamically focused jet of atomized particles onto a substrate. The material atomization is accomplished using a proprietary ultrasonic/pneumatic system [119]. The motion of the material stream is directed to the nozzle using a primary gas flow and then directed/shaped using a secondary gas flow. The actual motion of the jetting nozzle is controlled via multi-axis CNC programming [72]. Once deposited, the ink patterns undergo some form of post processing which may involve baking, sintering or UV light curing. In some instances, the UV curing mechanism and/or sintering mechanism (laser source) are built into the processing chamber allowing for immediate curing during printing [44], [120]. There are several benefits to the process which include the ability to operate at room temperature, the ability to tolerate a large distance from the substrate (i.e. contactless), the ability to print in multi-directions and multi-angles (including upward), the ability to control the print width by varying the secondary gas flow and the variety of materials which can be atomized and jetted [72]. An example of several conductive structures printed on a non-planar surface is shown in Figure 3. However, owing to the thin nature of the printed ink, Aerosol printing is not suited for printing voluminous structures and is often used in conjunction with other 3DP processes such as SLA or FFF. Also, because of its proprietary nature and specialization of the processing equipment, Aerosol printing is currently a very expensive process.

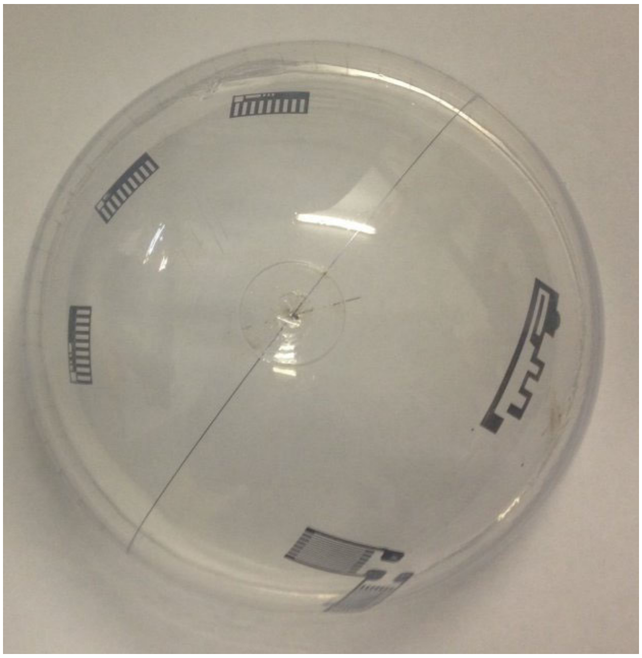

FIGURE 3. Aerosol Jet^{TM}printed creep sensor, antenna and strain gauge (reproduced with permission from Optomec).

There are several variables whose combinations affect print quality and these include the nozzle distance from the substrate, the nozzle size, the aerosol droplet size, the atomization pressure and the secondary (sheath gas) pressure [118].

Additional factors would include the print speed, ink and substrate temperature. These factors would affect the overspray of the jetted material and the thickness of the printed part and would be optimized based on the ink being jetted, specifically the ink viscosity, solvent and particle size and the target substrate being used [72], [118]. Various materials can be processed using Aerosol printing including conductive, semiconductor, dielectric, adhesive and polymers. The materials are usually in the form of inks which can have a wide range of viscosities. These suspensions include silver nanoparticles, carbon nanotubes, alumina and strontium titanate [121]. Multimaterial streams which combine materials have also been reported, these include combinations of silver and copper particles [25]. Another challenge with Aerosol printing is that the ink rheology can vary with time as the printing proceeds [121]. The Aerosol printing method has been shown to be suitable for printing conductors with fine resolution onto non-planar surfaces. The quality of the printed conductors is affected by the underlying surface (unevenness and porosity which can result in shorts and defects) and the post treatment processes (sintering or heating which affects the conductivity) [122]. To improve the print quality some pre-treatment of the substrate surface may be necessary [119]. For post treatment, higher curing/sintering temperatures improve the metal bonding and by extension the conductivity of the printed conductors, however the underlying substrates may not be able to tolerate the high temperatures [121].

Another challenge for Aerosol printed conductors and structures are that the deposited layers are very thin. The thin deposits pose an issue for high current applications and high frequency applications. Aerosol printing has also been adapted to allow for the production of dielectric structures by the jetting of UV curable materials to build the substrate upon which metal nanoparticle inks are then jetted followed by sintering [72], [120].

2) FIBRE ENCAPSULATION

Fiber encapsulation involves the continuous enclosing of fiber strands into a flow of polymer material [3], [22]. The patents related to the fiber encapsulation process were filed by Markforged Inc. The process works by simultaneously extruding the fiber material from a feeder nozzle which is directly in line with the thermoplastic nozzle. The angle of the fiber nozzle allows for the fiber strands to be embedded into the flow of the molten polymer [22], [123]. The polymer material used for fiber encapsulation would include the standard thermoplastics associated with FFF 3DP such as PLA, nylon [3], [22]. The fiber materials which can be encapsulated include carbon fiber, copper wire and optical fibers. Since the fiber encapsulation method involves a modification of the traditional FFF printing process the equipment cost and complexity is not high. Figure 4 illustrates several prototype insoles printed using a Markforged printer using fiber reinforced nylon materials and featuring embedded conductors and sensors.

There are two major applications for fiber encapsulation, the first is the creation of reinforced 3D printed structures to improve mechanical properties and the second is the creation of electrical conductors that have greater current carrying capacity [61]. The major benefit of embedding conductor strands into the dielectric substrate is the superior electrical properties of the conductor as compared to printed conductive organic inks, nanoparticle inks and pastes and conductive polymers. Solid wires would demonstrate lower resistance and greater mechanical strength. There are however several challenges with the fiber encapsulation techniques as relates to the embedding of conductive fiber such as copper wire. These challenges include the ability to bend the embedded fiber around sharp turns, cutting the fiber strand at intermittent points and creating joints between strands [61]. Finally, the process resolution and accuracy for EM related

TABLE 2. Summarization of key points for proprietary methods related to electrical & electromagnetic applications and research.

Method	Materials	Process overview	Proprietary/ open source	Advantages	Disadvantages
Fibre encapsulation	Thermoplastics and fibre materials	Fibre material is fed into a flow of molten polymer to form a coaxial composite	Proprietary	Solid wire and polymer printed simultaneously, superior conductivity and current capacity. Lower material cost.	Limited bend radius possible. Vertical conductors and joining conductors difficult. Fine wire diameters restrictive.
Ultrasonic embedding	Fibre materials	Ultrasonic tip melts the underlying substrate allowing for embedding of fibre		Solid wire provides superior conductivity and current capacity. Lower material cost.	Limited bend radius possible. Vertical conductors and joining conductors difficult. Fine wire diameters restrictive. Slower print speeds.
Aerosol/Nanojet	Nanoparticle inks	Nanoparticle ink is atomised into an aerosol and jetted onto substrate		Wide variety of materials, good resolution, fast print speeds, multimaterial capable	Post processing required, expensive, Conductive structures show higher resistance than traces.
Wire embedding	Fibre materials	Heated tip melts path in underlying substrate fibre is embedded	Proprietary and Open source	Solid wire provides superior conductivity and current capacity. Lower material cost.	Poor resolution and surface finish, limited bend radius possible. Vertical conductors and joining conductors difficult. Fine wire diameters restrictive. Slower print speeds.

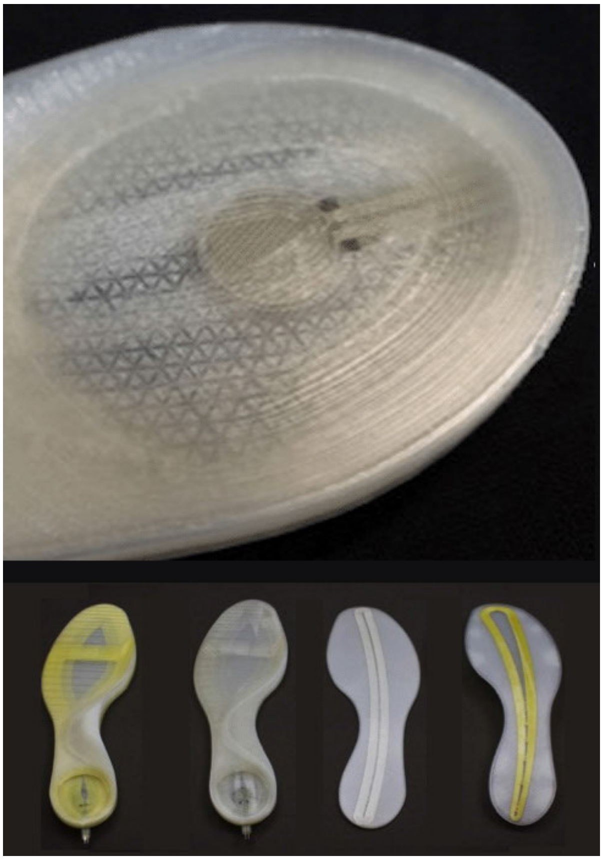

FIGURE 4. **Example 3D printed insole with embedded conductors and electronics (reproduced with permission from Markforged).**

applications are poor and the fine tuning of the process parameters to improve performance is ongoing [124].

3) WIRE EMBEDDING (ULTRASONIC EMBEDDING, JOULE HEATING)

While fiber encapsulation allows for the co-extrusion of fiber strands with a molten polymer matrix, processes which allow for the specific embedding of conductor strands into thermoplastic substrates have been patented by researchers at The University of Texas at El Paso (UTEP) [69]. Separately, an attempt was made to produce a basic, open source platform named SpoolHead that would allow for the embedding of wire conductors into a thermoplastic substrate [125]. The process is termed wire embedding and involves the guided embedding of conductor strands into the thermoplastic substrate using ultrasonic or joule heating [122]. The ultrasonic embedding method utilizes a high-power ultrasonic energy source with a modified exponential horn tip to allow for the guiding of the wire strand while keeping the surface planar. The joule heating embedding technique involves the use of an electrical current in the wire strand to increase its temperature and allow for embedding into the thermoplastic substrate. Like fiber encapsulation, the wire embedding technique is a modification to the existing FFF printing process. The wire embedding technique was created to directly address the challenges with creating conductive structures using inks, pastes and particle loaded polymers. These problems include high resistance, inconsistency across the length of the structure (which can lead to localized heating) and poor mechanical strength [44]. Another key benefit of the wire embedding approach is the comparative cost of using copper wire compared to the cost of conductive inks, pastes and polymers [61].

There are several challenges with the wire embedding process which are similar to fiber encapsulation, these include the need to maintain a smooth surface finish to the substrate after embedding, the ability to join wire strands to create junctions and the possible bending angle that can be achieved [122]. The use of laser welding was reported for wire joining [61]. A benefit of the wire embedding technique is that it allows for the embedding of a range of wire gauges (24-40 gauge). However, the large wire gauges required more energy which can create more localized heating to the substrate and create instances of surface warping and deformation. The higher current carrying capacity which the embedded wires allow also raises questions surrounding the breakdown strength of the thermoplastic substrate as well as heat dissipation with densely packed conductors [126]. Like fiber encapsulation, research work is on-going to improve the capabilities of the wire embedding processes [127].

B. TRADITIONAL TECHNIQUES

Many of the surveyed research efforts and commercial solutions utilized to create complete electrical structures and systems using 3DP techniques use some manufacturing methods which are associated with traditional printed methods. The methods used include lamination, spin-coating, stencil printing, gravure, air brushing, hand painting, plating and sputtering. Key information regarding the traditional printing methods is summarized in Table 3.

1) LAMINATION

The process of lamination involves the application of a thin sheet of material to a structure using various bonding methods including adhesives, welding, heat or pressure. The common sheet materials include metal foils and dielectric polymer sheets [3], [128]. The sheet material is usually added to the surface of a 3D printed substrate to form an even surface for further processing or to provide a conductive layer that can be further processed.

2) SPIN-COATING

The process of spin-coating is utilized to create very precise, thin, and uniform films of material onto a substrate. When applied to 3DP, the substrate is usually a printed thermo polymer and the applied material is in the form of a conductive or dielectric ink. The viscosity of the ink, solvent volatility and the angular speed of rotation help to determine the thickness of the film produced [129].

3) STENCIL

The stencil printing process involves the selective deposition of material onto a substrate using a squeegee. The stencil controls where the material is deposited onto the substrate. When applied to 3D printed structures the substrate is usually a planar printed structure and the stencil printing is used to add conductive, insulative and dielectric patterns to the substrate surface. The process works with materials which are either pastes or inks [130]. Variations of the stencil printing process involve the deposition of material into channels which have been pre-cut into the underlying substrate [91]. After deposition the material is cured using either UV light or heating. In the case of heating some variation in part dimensions may result due to shrinkage. One example of a commercial developed system geared toward electrical structures has been produced by EoPlex Technologies Inc. and is called high volume print forming (HVPF). A wide variety of materials can be processed using the stencil printing method including alumina, silica, nickel, iron, stainless steel, palladium, zirconia, glass, silver and gold [103].

4) GRAVURE

Gravure printing is a very high-resolution, high-volume printing process which is particularly suited to produce patterns onto a flexible substrate. The process involves the use of a metal cylinder which is etched with the desired pattern, ink material is then fed onto the face of the cylinder and then rolled onto the surface of the substrate. The gravure process can produce thick structures and is suitable with high viscosity inks and pastes, it is not cost effective for small production volumes [23].

5) AIRBRUSHING

The process of airbrushing and its variant, electrostatic spray deposition (ESD), involves the creation of a fine stream of droplets using air pressure and/or high voltage discharge which is directed onto a substrate [131]. The equipment used for airbrushing is widely available, low cost and the process can be performed at room temperature but more complex and expensive setups are used for various electrospray methods [132]. The simplest methods involve the retrofitting of a standard FFF printer technology to allow for the directing and triggering of the airbrushing system. The process is most often used to create conductive and dielectric films on non-planar and non-uniform surfaces. The materials which have been applied using airbrushing include metal nanoparticles such as aluminum and polymer materials. The airbrushing process easily allows for the control of the localized thickness and uniformity of the printed film [132]. The major limit to the application of air brushing is the ability to create fine detailed patterns. The use of removable masks has been proposed as one technique for improving the patterning resolution. Another method involves the precision control of the electromagnetic field to control the material stream [131], [132].

6) HAND PAINTING

The technique of hand painting is used primarily for adding conductive layers to geometrically complex structures [133]. The materials which have been used with hand painting

TABLE 3. Summarization of key points for traditional methods applied to electrical & electromagnetic applications and research.

Method	Materials	Process overview	Proprietary/ open source	Advantages	Disadvantages
Lamination	Conductive or dielectric sheets of materials	Material sheet is pre/post cut and laminated onto a 3D printed substrate	Open source	Good conductivity, fast	Adhesion limited based on the surface roughness of the 3D printed substrate. Limited to planar designs. Limits to the resolution of the laminate object. Greater material wastage.
Spin-coating	Conductive and polymer inks	Ink is deposited onto the substrate and spun to the required thickness	Open source	Fast, uniform thickness	Post processing is required in some instances. Works best with smooth, planar surfaces.
Stencil	Variety of inks and pastes	Masks are precision cut and used to selectively apply the inks and pastes to the substrate	Open source	Fast, low cost	Post processing is required in some instances. Works best with planar surfaces. Greater material wastage.
Gravure	Variety of inks and pastes	The desired pattern is engraved onto a cylindrical plate and the ink/paste is transferred onto the substrate	Open source	Fast, well suited for high volume	Expensive setup costs. Works best with planar surfaces. Post processing is required in some instances.
Air brushing	Variety of inks	CNC controlled air brush tool	Open source	Low cost, conductive and polymer material options	Poor resolution. Works best with planar surfaces. Conductive structures show high resistance
Hand painting	Variety of inks and pastes	Hand application of material using an applicator	Open source	Low cost, wide variety of materials, easy application to non-planar surfaces	Poor resolution. Post processing required in some instances. Poor repeatability.
Plating (e.g. electro deposition)	Specific chemical solutions	Electrode and electrode less transfer of metal onto substrate surface	Open source & proprietary methods	Strong plating finish, good electrical properties	Risk of contamination. Slow speed. Surface activation necessary, works best with continuous surfaces.
Sputtering	Metallic elements, alloys and ceramics	Particles ejected from sacrificial target and deposited on substrate	Proprietary methods	Precise thin layers possible, good replication of bulk material properties	Limited material options. Not suitable for large material build up. Slow speed. Expensive.

include silver, copper and gold pastes and inks. The process was found to provide improved conductivity when the materials are applied in multiple layers [134]–[136].

7) PLATING (E.G. ELECTRO DEPOSITION)

There are several processes which fall under the umbrella of plating, these include electrodeposition, autocatalytic plating and, electron beam evaporation [116], [137]. Plating is most often used to apply a conductive coating to a 3D printed structure. The plating process is able to grow structures in a variety of shapes and sizes and can be applied to complex 3D printed substrates [133]. In addition, using techniques such as micropipette, micro and nano scale conducting structures can be created [116]. Commercial systems have been developed by Microfabrica Inc. under the name MICA Freeform which allow for the growth of complex 3D structures [103]. Several materials have been utilized with the plating processes including nickel, nickel-cobalt, platinum, copper and gold.

The electrodeposition and autocatalytic processes can be performed at room temperature and ambient conditions. One challenge of the plating processes is the need to activate nonconductive surfaces (such as polymers) to allow for plating [138], [139]. The challenge with the activation process is the peel strength of the plated layer which can result in a coating that can easily crack and flake under mechanical deformations. The benefit of the activation process is that metallization would only occur on those surfaces which had been activated [139]. Another benefit of these processes is that the deposited material is pure thus providing superior conductivity. For the electron beam transfer process, a stream of electrons is directed to a donor source which induces the source to melt and discharge particles toward the target substrate. Unlike electrodeposition and autocatalytic plating, electron beam transfer requires vacuum conditions and is much more complex and thus more costly [137]. It is important to note that the plating processes may require post processing in the form of etching to remove unwanted material build up [103].

8) SPUTTERING

The sputter deposition process is similar to electron beam transfer in that a source material is forced to eject particles which are deposited onto a target substrate. In the case of sputtering the material ejection is induced by a gas plasma (e.g. Argon) [114]. The process is able to produce thin uniform films of a wide variety of materials at temperature well below their melting points. However, the equipment is highly specialized requiring a vacuum environment and is thus very expensive. It is also very difficult to control the direction of deposition thus requiring post etching [140]. Sputtered films have also been reported as demonstrating poor adhesion to 3D printed substrates resulting in delamination [117].

C. EXOTIC

Exotic techniques are examples of very specialized 3DP processes which have been applied to the production of electrical structures. The two processes reported in the research are laser induced forward transfer (LIFT) and laminate object manufacturing (LOM). Key information regarding the exotic (highly specialized) techniques is summarized in Table 4.

1) LASER INDUCED FORWARD TRANSFER (LIFT)

Laser induced forward transfer (LIFT) can also be referenced as directed energy deposition (DED) and encompasses a set of processes which utilizes an energy sources such as a laser, electron beam or electric arc to project material from a source onto a target substrate [44], [141]. The family of processes is able to utilize a very wide variety of materials both solid and liquid and is able to achieve very fine details. The ability to work with a variety of materials provides the opportunity for entire composite electrical structures (organic materials, conductors, dielectrics) and complete electrical systems to be produced [142].

2) LAMINATE OBJECT MANUFACTURING (LOM)

Laminate object manufacture (LOM) is based on the traditional method of material lamination where sheets of material are laid and bound to the existing stack and the layer is selectively trimmed before adding the next layer and repeating the process to build the desired 3D structure [2]. An example of a previously available LOM system is the Solido printer system [23]. The main variations in the process are the types of sheet materials (paper, dielectric, metal) the method of trimming (mechanical cutter, laser) and the methods for binding (adhesives, thermal bonding, ultrasonic welding, brazing) [143]. Figure 5 shows a laminated structure built using an ultrasonic bonding method known as Ultrasonic Additive Manufacturing (UAM). In the example, a fiberoptic cable has been successfully embedded within the laminated metal sheets. In some cases, post machining may be necessary to achieve the desired surface finish and improve dimensional accuracy [44]. One challenge in using this process for building electrical structures is the need for maintaining a level surface for each subsequent layer [23].

D. OTHER (SUPPLEMENTAL)

There are several manufacturing techniques which were frequently referenced in the surveyed literature which were often used in conjunction with 3DP to produce electrical structures but which are not 3DP processes. These processes include micro-machining, laser ablation and the use of low melting metallic alloys. Key information regarding these other (supplemental) techniques is summarized in Table 5.

1) MICRO-MACHINING

Micro-machining can refer to a group of processes which aid in the controlled removal of material to create detailed features and/or to improve the dimensional accuracy of a 3D printed structure. There are many examples of micro-machine processes including electro-discharge micro-grinding (EDG) where two processes (electro-discharge and grinding) work together to achieve material removal and laser assisted micro milling where the laser energy helps to weaken the material and the removal (milling) [144]. In the creation of electrical structures, micro-machining processes are often used to produce channels in the printed substrate which can accommodate conductive materials. The use of channels allows for higher conductor density by preventing ink/paste spreading, improved surface finish which aids in the deposition of subsequent polymer layers and allows for greater conductor cross-sectional area which lowers resistance [122]. These techniques are also used to create multilayer channels which can be filled with material to achieve vertical connections. Finally, these processes have frequently been used to produce recessed pockets for the embedding of discrete components [145]. A major challenge for these processes is the need for highly skilled staff to coordinate the often complex machining processes and the need for many cleaning phases to remove waste materials.

2) LASER ABLATION

Laser ablation is a specific material removal process which involves the use of directed laser energy to produce channels and vias into the 3D printed substrate material [146]. The laser ablation process allows for good resolution and process control of width and depth of cutting through the manipulation of the laser energy and because it is a non-contact process (as compared to micro-machining) intricate geometries can be cut [122]. The challenges with the process include compatibility with the substrate material and the difficulty of removing soot and residual waste. The difficult soot and waste removal is particularly problematic since laser ablation of the substrate often requires multiple passes to achieve the desired cross-section. The presence of waste materials can impede the subsequent laser cutting. Therefore, there is a need for more frequent cleaning steps and this increases the likelihood of contamination and has the additional challenge of realigning the substrate after each cleaning stage [147].

3) LOW MELTING METALLIC ALLOYS

Low melting metallic alloys are a group of materials which feature low resistance and are in a semiliquid/paste form at room temperature allowing for them to be easily extruded and shaped without the need for machining or high processing temperatures. The metallic alloys are used with 3D printed substrates in order to build electrical structures. The choice of substrate material such as ceramics, gels and resins also allow for a variety of end applications. Two of the most common materials used with the metallic alloys include gallium and indium [148]. There are also many low melt solder alloys which include combinations of materials such as lead, silver, tin and bismuth [149]. Since the low melting metallic alloys remain relatively soft and/or in a semiliquid state at room temperature their use in building 3D printed electrical structures requires that the substrate material is either printed with receiving channels or channels are cut post processing using milling processed into which the low melting alloys would be injected/filled [150]. The semi-liquid nature of the alloys also makes them suitable for flexible electrical applications which use soft polymers and elastomers to encase the metallic alloys [151], [152]. One significant disadvantage of these materials is that they are fairly costly [116].

E. COMPOSITE TECHNIQUES

Many of the 3DP techniques which have been discussed previously have been identified as being suitable for specific materials and specific applications. For many end use application scenarios which involve the construction of electrical structures there is often no single 3DP technique that can be utilized to produce the completed structure [153]. This is particularly true for electrical structures which are intended for end applications versus prototypes. Therefore, many 3DP solutions for producing electrical structures are composite techniques which incorporate multiple 3DP processes and/or traditional printing techniques and/or non 3DP methods [91], [109]. In some instances, the idea is not to produce the entire electrical structure using 3DP but to incorporate traditional electronics manufacturing techniques as well. An example of this is the inclusion of traditional electronics materials and components into a fully integrated electrical structure which is produced by the process [154], [155]. Another application would be the introduction of a variety of materials with different functionalities including thermal, conductive, dielectric, shielding, optics, flame retardance [122]. The desired goal would also be that the many materials and techniques are seamlessly integrated in such a way as to minimize human intervention in the overall process [81], [156]. The challenge with these combination methods is their ability to match the traditional electronic manufacturing methods in terms of the reliability

TABLE 4. Summarization of key points for exotic (highly specialized) techniques applied to electrical & electromagnetic applications and research.

Method	Materials	Process overview	Proprietary/open source	Advantages	Disadvantages
Laser induced forward transfer (LIFT)	Metallic elements and polymers	Laser pulse ejects material from a donor onto a target surface	Proprietary methods	Meso- and microscale structures possible, good replication of bulk material properties	Limited material options. Many process parameters are unknown. Expensive
Laminate object manufacturing	Paper, polymer sheet, metal sheets	Material sheets are precision cut and overlaid with adhesive	Open source	Wide variety of materials in sheet form, large parts are simple to produce	Poor resolution. Poor mechanical strength. Metal processing is difficult and rare

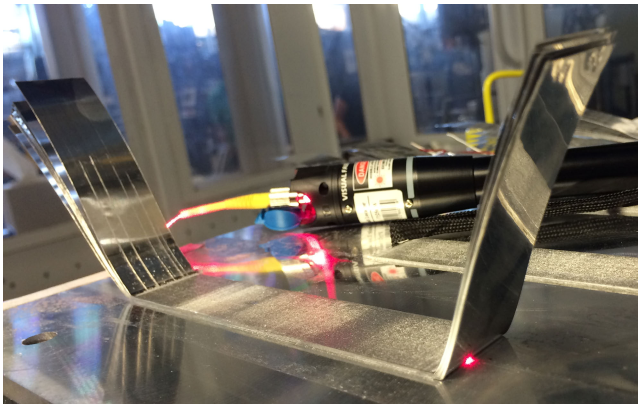

FIGURE 5. Example composite metal structure featuring an embedded fiberoptic cable produced using ultrasonic additive manufacture (reproduced with permission from Fabrisonic).

and aesthetics of the completed electrical structure [31]. This challenge remains the main barrier preventing the 3D printed structures from being adapted as end applications. For the remainder of this section, several documented combination methods of electrical structures production and their limitations will be described. These methods are based on three common configurations identified from examining the literature.

1) COMBINATION 1

One of the most utilized combinations for building electrical structures is the use of conductive paste/ink extrusion and FFF or SLA printing [28], [77], [82], [109], [157]–[161]. In some instances, CNC milling/laser ablation is used to cut channels into the 3D printed substrate to allow for a more level surface and better precision [44], [69], [122]. The conductive materials can also be injected into enclosed channels built into the 3D printed substrate [162]. CNC technology can also be used in the form of pick and place techniques to position discrete electronic components into the structure [91], [122]. An example of a hybrid system produced by nScrypt is shown in Figure 6. The system includes FFF printing capability, paste extrusion, milling/drilling, pick and place and a host of other integrated capabilities.

There are several key challenges and limitations to this combination approach. Conductive inks and pastes which require post treatment involving heating and/or sintering must have low-temperature curing capabilities in order to be compatible with the 3DP processes but the low-temperature curing materials tend to have poor conductivity [63], [122]. This problem is significant for SLA printed substrates [126]. There are at present several high temperature polymers which can be used with FFF. Another issue is the presence of gaps in the substrate which can lead to the applied inks and pastes bleeding leading to shorts. SLA printed substrates generally do not possess gaps and can avoid this issue [23]. Some methods for addressing this issue include baking the substrate to reduce the presence of gaps and applying an additional layer of material to seal the surface of the 3D printed structure. The combined process techniques also typically involve very long production times due to the need to switch between manufacturing processes and in some instances shift the electrical structure between manufacturing platforms [77]. The pause between the printing processes would allow for material cooling and weaker interlayer bonding resulting in structural weakness [63].

The flatness of the 3D printed substrate surface (particularly with FFF printed structures) is a problem that affects the subsequent extrusion of the conductive patterns [63]. There are several methods adopted for compensating for the surface imperfection these include milling the surface and scanning the surface to adjust the extrusion height to compensate for the uneven surface [23]. Another method used to compensate for the surface roughness as well as the sintering temperature and to reduce inter-process pauses is the printing and sintering of the conductive pattern onto a thin film which is then transferred to the 3D printed substrate. The film would feature a high glass transition temperature allowing for higher sintering temperatures and the printing pause is reduced to the time taken to transfer the film to the substrate [63]. Finally the insertion of traditional electronic materials and components also presents a challenge due to the large tolerances in the dimensions of the components which increases the difficulty of accurate placement [91]. The issue of accuracy and resolution is most restrictive for FFF in combination with extrusion due to the possible nozzle diameters and slicing software capabilities. Specifically, the 3D geometry, component spacing and conductive trace spacing need to be multiples of the nozzle diameter to effectively produce the 3D printed electrical structure [82].

TABLE 5. Summarization of key points for other (supplemental) techniques applied to electrical & electromagnetic applications and research.

Method	Materials	Process overview	Proprietary/ open source	Advantages	Disadvantages
Micro-machining	Metallic, polymer and ceramic stock materials	Meso- and micro scale drilling, milling and cutting of bulk material	Open source and proprietary methods	Well established machining techniques. High repeatability	High start up capital costs
Laser ablation	Metallic, polymer and ceramic stock materials	Material removed through the application of laser pulses	Open source and proprietary methods	Good process control, capable of deep precise cuts.	High start up capital costs. Some issues with surface finish
Low melting metallic alloys	Specific metal alloys with low melting points	Liquid metal is printed onto substrate surface or injected into channels in substrate	Open source and proprietary methods	Some low-cost options,	Risk of contamination in some cases.

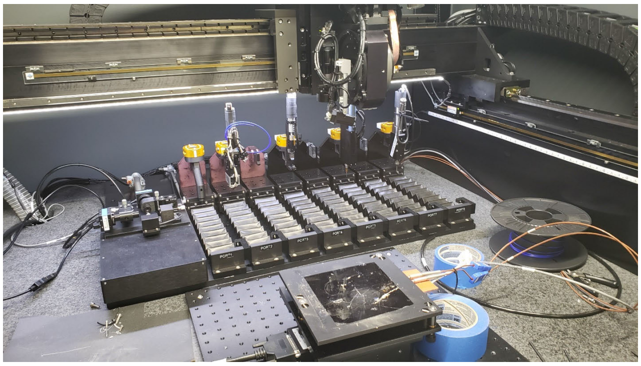

FIGURE 6. Example combination solution featuring interchangeable heads including extrusion, micro-dispensing, milling/drilling, pick and place, laser processing, UV processing, machine vision (reproduced with permission from nScrypt).

2) COMBINATION 2

Another combination of processes which is used particularly for high current applications is the use of wire embedding in combination with FFF or SLA 3DP of the substrate and the pick and place insertion of discrete electronic components [25], [31], [44], [153]. A variation of this process involved weaving the wire strands into fabric in combination with the FFF printing method [163]. The wire embedding method also provides additional mechanical strength to the 3D printed structure [122]. While the method is effective when embedding wire in the x-y plane it is not simple to build vertical connections.

3) COMBINATION 3

One popular combination involves combining 3D material jetting or Aerosol jet printing with FFF or SLA printing where the 3D material jetting is used to produce the conductive patterns [25], [44], [108], [109], [119]. There have also been reports of binder jet 3DP used in conjunction with Aerosol jet printing to produce electrical structures [164]. The process required a special vacuum system to remove the unbound powder in the component cavity before part insertion. Attempts have been made to utilize PBF in conjunction with Aerosol jetting and extrusion dispensing to produce 3D printed electrical structures [103], [165]. The layers of ink dispensed in all of these systems is typically very thin (2μm) and traditional soldering techniques cannot be used for attaching components (e.g. press fit, wave soldering, standard temperature reflow) [119].

IV. 3D PRINTED STRUCTURES

In much of the surveyed literature involving EM related applications and research, attempts have been made to build electrical structures in order to validate the specific 3DP technology. Based on their prevalence in the literature, several categories of electrical structures were identified:

- Complete electrical structures (CES)
- Conductive structures (CS)
- Sensors
- Antennae
- Passive components
- Waveguides
- Dielectric structures

Figure 7 illustrates the reported frequency of the electrical structure types as well as the extent of utilization of each of the 3DP technologies. In the previous sections (Sections 2-3) each of the 3DP technologies were considered in depth based on materials and process strengths & limitations. In this section, the different electrical structures categories will be considered based on the various types of 3DP technologies utilized to produce them. In addition, highlights of the specific 3DP technologies will be drawn from the previous sections and stated during the discussion. Finally, for each of the electrical structure types, specific examples of structures built by researchers within each category will also be cited.

A. COMPLETE ELECTRICAL STRUCTURES (CES)

For the purpose of the survey, the authors defined a complete electrical structure (CES) as any built structure which controlled the flow of electrical energy with a defined purpose. An example of a CES would be a simple 555 timer circuit [157]. As seen from Figure 7, CES type systems account for more than one quarter of the electrical structures built using various forms of 3DP technologies. Of the technologies utilized, composite processes (Comp) and proprietary processes (Pro) account for more than half of the reported CES work. Material extrusion (ME) was also observed to be used significantly with a utilization rate of approximately 15%. The dominance of Comp and Pro processes was not unexpected since the creation of complete CES structures would be difficult to achieve with a single 3DP technology. The relatively high utilization of ME can also be accounted for by the compatibility of ME with a broad selection of conductive and non-conductive materials. Fused filament fabrication (FFF), traditional print processes (Trad) and material jetting (MJ) accounted for the majority of the remaining reported work on printed CES structures (collectively 20% of reported work). A few instances of powder bed fusion (PBF) and stereolithography (SLA) were also reported (accounting for 4% of reported work). From the descriptions of the technologies in Section 2 of this survey it can be appreciated that the low utilization of the aforementioned 3DP technologies may be attributed to the inability to produce satisfactory conductive structures (poor resolution, high conductivity: FFF, PBF, SLA) or significant challenges faced in order to process both conductive and non-conductive materials (slow print speeds, material durability SLA, PBF, MJT). It was noted in all of the reported work on the production of CES structures that full functionality required the integration of traditional electronic components into the 3D printed structures.

There are several distinct and noteworthy CES structures which were described in the literature. Many teams reported the implementation of a 555-timer circuit with a blinking LED. In a few instances, the reported 555-timer circuit was built using a single 3DP technology e.g. FFF [139]

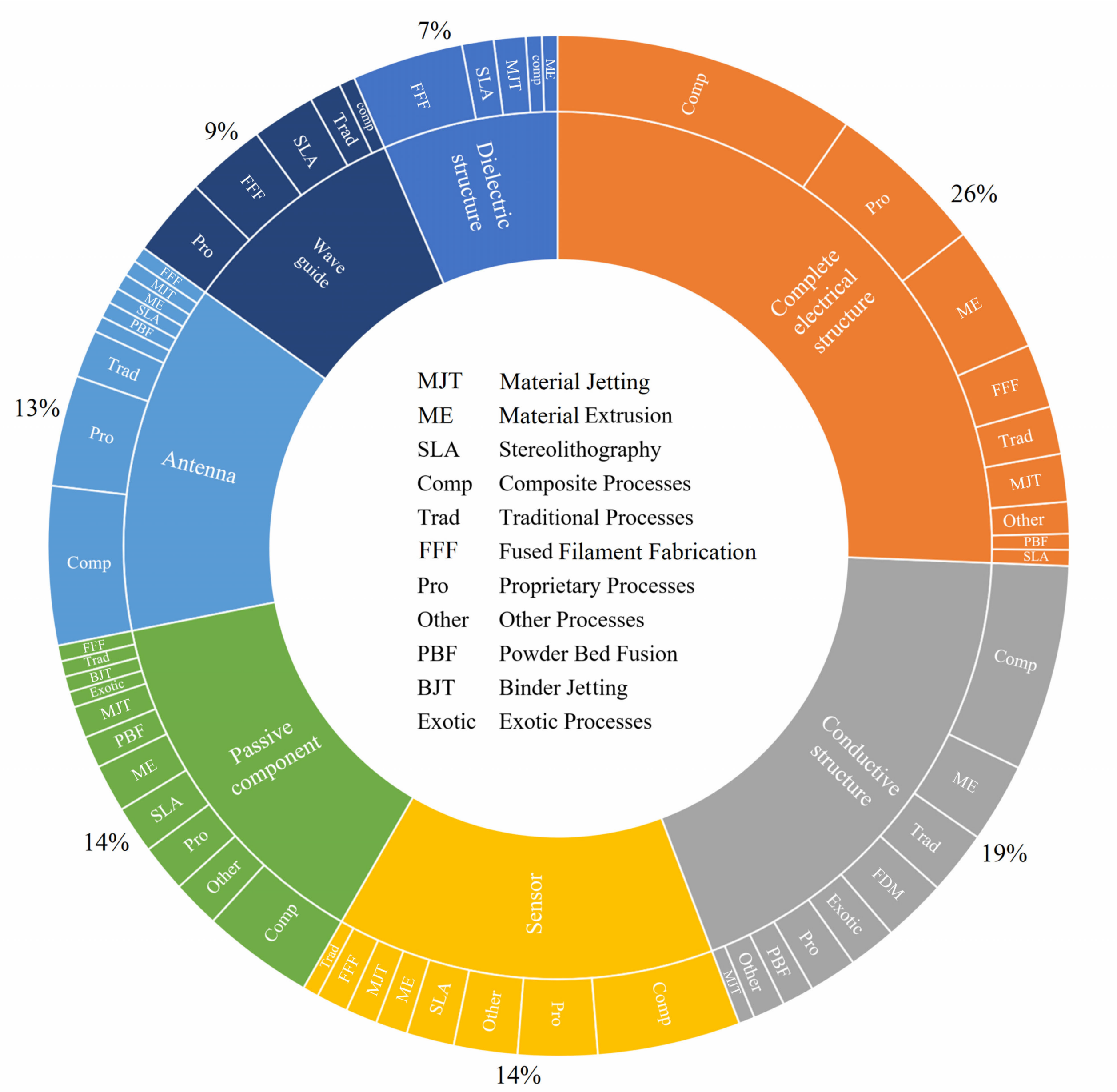

FIGURE 7. Distribution of the instances of reported common 3D printed electrical structures and their applied 3DP methods in the surveyed literature.

and ME. The majority of implementations of the 555-timer circuit involved composite 3DP processes combining SLA and/or FFF and ME [23], [150], [157]. Variants of the 555-timer circuit were also reported e.g. a thermistor implementation [158]. Finally, several teams reported novel 3D shapes of the 555-timer circuit including cuboid [82] and pyramid [109]. Another popular built CES structure was energy storage structures/batteries [166]–[168]. One common battery type was lithium ion. Teams reported implementing interdigital lithium batteries using ME [169], coin cells using FFF [57], high density batteries using SLA and ME [170], [171]. Work was also reported for the implementation of graphene batteries using ME [172], [173]. Finally, work was reported on the use of FFF to produce a novel redox battery [174]. There were several other examples of novel built CES structures. Implementation of solar cells using MJT were reported by various teams [44], [73], [167], [175]. Satellite units were also building using composite 3DP processes combining SLA, ME and proprietary techniques [122], [176]. Flexible robotic limbs were also implemented using composite combinations of SLA and ME [44], [160]. Work was also reported for the creation of light sources which included LEDs and electroluminescence created using MJT and ME printing [73], [92], [160], [167]. Finally, various research teams reported on the implementation of electro responsive systems including an electroactive switch [177], a loudspeaker [61] and a 3-phase brushless DC motor [69].

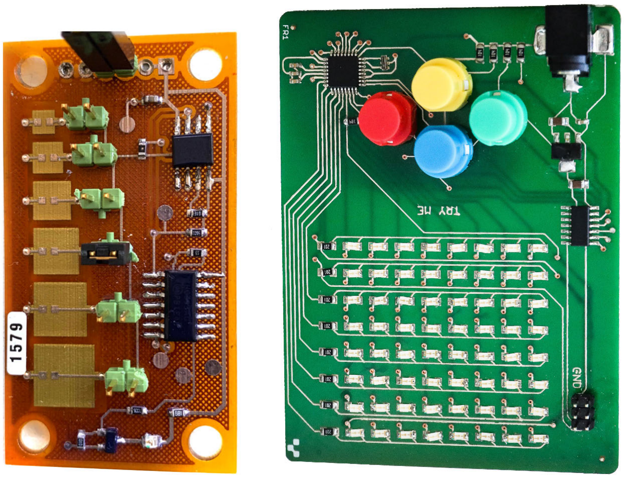

FIGURE 8. **(a) Example capacitor circuit produced using material jetting printing (reproduced with permission from Nano Dimension); (b) Example LED Matrix game with conductive traces printed onto an FR4 substrate using extrusion printing (reproduced with permission from Voltera).**

There are numerous examples as reported in the literature of unique CES built structures which were produced by research teams using 3DP. Figure 8 illustrates two CES example. The first system is a capacitance circuit featuring various printed capacitors produced using a Nano Dimension Ltd hybrid 3DP system which utilizes MJT for jetting of silver nano-particles (conductive) and photocurable acrylate polymers (dielectric) [178]. The second system shown in Figure 8 is a LED matrix game which was produced using a ME printer system produced by Voltera Ltd. Deffenbaugh produced a camera system [23] and MacDonald et al produced a gaming die using SLA for the substrate and ME for the interconnections of electronic components [31]. A glove with built in strain sensor and circuitry was produced using FFF and MJT [160]. The frame and battery for an LCD sunglasses concept was produced using FFF [57]. The capacitive buttons for a concept computer mouse was produced using FFF [179]. Several researchers reported implementations of sensor concepts with supporting circuitry including a magnetometer system [156], light sensing [159], RFID system [180] and a smart bottle cap for detection of spoilt milk [162]. Finally, Mannoor et al reported on the integration of tissue with integrated electronics in their implementation of a bionic ear using ME technology [181].

B. CONDUCTIVE STRUCTURES (CS)

For the purpose of the survey, a conductive structure (CS) was interpreted as any built structure which acted solely as a conductor. An example of a CS would be a microstrip [23]. CS 3D printed structures represented 20% of the built electrical structures in the surveyed literature. Composite processes (Comp) were the major technologies utilized and accounted for 35% of the surveyed work on CS structures. The other major 3DP technologies reported are material extrusion (ME) and fused filament fabrication (FFF) which accounted for 25% of the built CS structures. Traditional print processes (Trad) were also shown to have significant use with 10% of uptake. Exotic processes were also significant with an 8% utilization. The heavy use of traditional and exotic processes can be accounted for by the difficulty to produce metallic structures using 3DP processes.

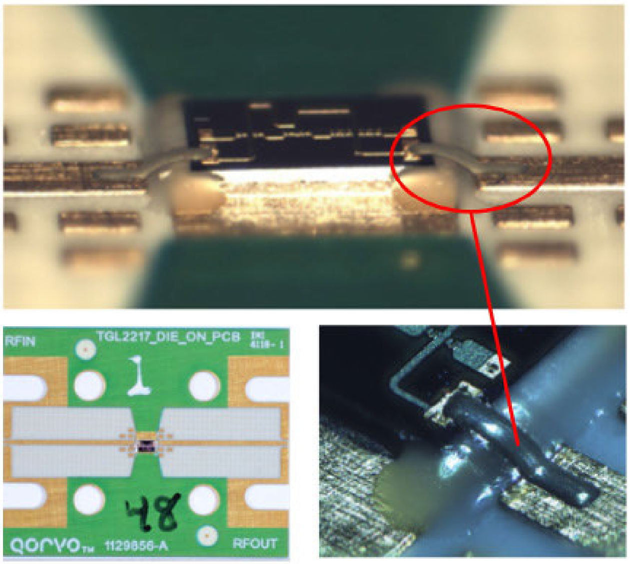

FIGURE 9. **Image showing a test board with silver nanoparticle interconnect Aerosol Jet$^{\text{TM}}$printed on a gold bonding pads (reproduced with permission from Optomec).**

There has been significant emphasis placed on the research into conductive structures due to the challenge of producing these structures using 3DP technologies. One of the most replicated CS structures in 3DP EM related research is a conductive trace. Many teams reported the implementation of conductive traces using Composite 3DP technologies including combinations of SLA and ME [23], [91], [95], [109], [146], [157], ME and proprietary Aerosol printing [118], [165], FFF and proprietary Aerosol [119], FFF and traditional airbrushing [131], [133], and FFF and traditional plating [133], [177]. Figure 9 illustrates an interconnection implemented on a curved surface using Aerosol printing. Implementation of conductive traces was also reported using MJT printing [182], ME printing [55], [97], [183], [184] and SLA printing [185]. There were also several examples of the use of other (supplemental) techniques for the creation of conductive traces. One reported technique involved the injection of low temperature melt metal alloys into printed channels [44], [150]. Another reported method involved a modified FFF process for the printing of low melt metal solder to produce conductive traces [149]. Finally, highly specialized processes such as electrodeposition [186] and laser induced forward transfer [142] were adapted for printing of conductive traces.

Other unique conductive structures were implemented using 3DP printing techniques. The implementation of conductive component holders was reported using FFF printing [187] and a composite method combining SLA and traditional plating [111]. Electrode structures were implemented

TABLE 6. **Examples of high-resolution conductive structures.**

High resolution conductive structures	3DP Technology	Reported Work
TFT Transistor circuits	MJT	[73]
MEMS printed structures	SLA, SLS	[103]
FET transistors	MJT	[81]
Transistor	Composite-MJT, Spin coating	[79]
Transistor	MJT	[164]

using ME printing [188] and a composite method of SLA and traditional plating [114]. Researchers also reported on work implementing the 3DP of high power CS structures using combined processes of SLA, FFF, ME, PBF and traditional plating [189]. There are also several instances of proprietary work related to the implementation of CS structures including the embedding of solid metal conductor into an FFF printed substrate [126] and the implementation of a transparent conductive film [160].

Finally, in the surveyed literature there are several examples of very high-resolution copper structures which were produced using 3DP technologies. Examples of the high-resolution structure types, 3DP technologies and reported work are captured in Table 6.

C. SENSORS

For the purpose of the survey the authors have interpreted a sensor as any built structure designed to monitor and respond to a particular phenomenon. Sensor structures account for 14% of the built electrical structures. Figure 10 shows examples of a temperature & humidity sensor and a touch sensor as implemented by the researchers at Phytec Ltd. using MJT in combination with EP. Composite printing (Comp) processes were found to be the major 3DP processes used for sensor implementation with a utilization of 32%. Proprietary 3DP methods accounted for 18% of the fabricated sensors. There was also significant use of processes such as milling, and low melt metals (i.e. other (supplementary) processes) which accounted for 14% of surveyed work. The dominance of Comp, proprietary and other processes can be attributed to the general structure of a generic sensor which typically consists of a dielectric substrate and a well-defined conductive pattern. It is difficult for any single 3DP technology to be able to process the variety of materials needed to produce such structures hence the prevalence of composite and proprietary methods. The remaining 3DP technologies which accounted for the built sensor structures include FFF, MJT and ME each of which had equal utilization. A popular sensor structure reported in the literature is the strain sensor. The prevalence of the strain sensor can be attributed to the difficulties faced in producing consistent conductive structures of low resistance. A by-product of the imperfect conductive structures is its natural characteristic of a variable response to strain which could be utilized in the implementation of a strain sensor structure. In addition to the category of strain sensors a wide variety of sensor types were produced using the 3DP technologies. Examples of the sensor types, 3DP technologies and reported works are captured in Table 7.

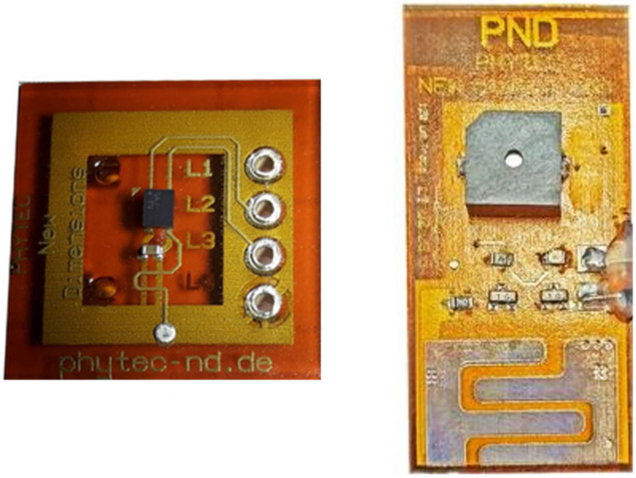

FIGURE 10. **Temperature & humidity sensor; touch sensor produced by Phytec new dimensions (reproduced with permission from Nano Dimension).**

D. PASSIVE COMPONENTS

For the purpose of the survey, a passive component (PC) was interpreted as any built structure which cannot control a current by means of an external electrical signal. An example of a PC would be a resistor. It is acknowledged that sensors and antennas can be considered to be a category of passive components but due to their prevalence in the surveyed literature they are considered (for this survey) as separate categories. Figure 11 shows two examples of 3D printed passive components. A USB powered inductive coil was implemented using MJT in conjunction with ME and a copper heatsink was printed using FFF followed by sintering. The implementation of passive components represents 14% of the reported work on built electrical structures. As with sensor, the structure of a 3DP passive component consist of an insulative substrate and well-defined conductive pattern. As noted with the sensor structures, a single 3DP technology typically cannot support the materials and processes characteristics required to produce a well-defined passive component. As seen in the literature, composite processes accounted for 26% of the built passive structures. EP, SLA, proprietary and other processes were equally utilized and accounted for 11% of utilization respectively. The remaining technologies reported were MJT, BPF, BJP and FFF. Table 8 records examples of the passive component types, 3DP technologies and reported work.

E. ANTENNA

For the purpose of the survey, an antenna was considered to be any built structure which is designed to be the interface between RF signals and electric currents moving in a conductor. An example of an antenna type is a dipole antenna. Figure 12 presents several examples of 3D printed antenna structures. A printed array antenna is shown which

TABLE 7. Summarization of sensor types, 3DP technologies and research work for 3D printed sensors.

Sensor Type		3DP Technology	Reported Work
Strain		FFF	[179], [34]
		ME	[93], [97]
		SLA	[185]
		Proprietary FEAM	[123]
	Composite	FFF, ME	[161]
		SLA, ME	[151]
		SLA, Proprietary Aerosol, Traditional print-stick-peel	[63]
		SLA, ME, FFF, Laser ablation	[147]
		FFF, Proprietary Aerosol	[190]
Light		MJT	[78], [44]
Pressure		MJT, Traditional spin coating and lamination	[128]
Pressure		FFF	[191]
Split & Close ring resonators		MJT	[71]
Flow		SLA	[110]
Liquid		ME	[192]
Ultrasonic		SLA	[104]
Magnetic Flux		FFF, Traditional micromachining, Proprietary Aerosol	[122]
Inductive		Proprietary FEAM	[61]
Temperature		SLA, ME	[108]
Capacitive		Proprietary Aerosol	[190]
Oxygen		Proprietary Aerosol	[193]

TABLE 8. Summarization of passive component types, 3DP technologies and research work for 3D printed passive components.

Passive Component Type	3DP Technology	Reported Work
Capacitor	MJT	[44]
	SLA	[44], [112]
	ME	[194]
	Composite - FFF, ME	[28]
	Composite - Proprietary Aerosol, PBF	[164]
	Composite - SLA, Low melt metal alloy	[162]
Inductor	ME	[96]
	Proprietary FEAM	[61]
	Composite - FFF, ME	[77]
	Composite - SLA, Low melt metal alloy	[162]
Resistor	ME	[195]
	Composite - SLA, Low melt metal alloy	[162]
	Composite - SLA, ME	[146]
Toroidal Core	FFF	[30]
	Composite - FFF, Traditional plating	[189]
Magnetic Ferrite Shape	ME	[89]
Rheostat	Composite - Proprietary FEAM	[61]
Insulating Spacer	SLA	[102]
Heatsink	ME	[189]

was designed by the University of South Florida (USF) for the U.S. Air Force (USAF). The array antenna was produced using a combination process of FFF and EP with milling capabilities [196]. A millimeter wave dipole antenna produced using Aerosol printing and a bowtie antenna which was produced using a combination of MJT and ME as also shown. The implementation of antenna structures represents 13% of surveyed work on built electrical structures. As was observed for the sensor structures, an antenna in its simplest form involves a dielectric substrate and well-defined conductive pattern. Also, as was observed for built sensors and passive components, composite 3DP processes represented the major technology reported in the literature with 38% utilization. The next major category was proprietary 3DP technologies with 27% utilization. The remaining technologies were FFF, MJT, ME, SLA, PBF and BJT all of which had equal utilization at 4%. Table 9 lists example antenna types, 3DP technologies and reported work.

F. WAVEGUIDE

For the purpose of the survey, a waveguide was considered to be a built structure designed to guide electromagnetic waves with minimal loss of energy. Waveguides represent 9% of the reported work on built electrical structures. Example waveguides which are built using 3DP technologies for operation above RF and microwave wavelengths (for example, optical wavelengths) do not generally require metallization of their surface [208]. Therefore, the built structures reported in the literature predominantly use FFF, proprietary and SLA technologies with 29%, 29% and 24% utilization respectively. Any metallization is applied post printing using a traditional method such as electrochemical plating. Table 10 records examples of the waveguides reported in the literature. Figure 13 illustrates the various sections of a WR15 (7.05-10GHz) rectangular waveguide which was produced using SLA 3DP followed by traditional electrochemical plating.

TABLE 9. Summarization of antenna types/frequency, 3DP technologies and research work for 3D printed antennas.

Antenna Type/Frequency	3DP Technology	Reported Work
Patch Antenna/5.8GHz	FFF	[197]
Patch Antenna/25GHz	Composite - FFF, ME	[198]
Patch Antenna/7.5GHz	Proprietary FEAM	[199]
Patch Antenna/2.4GHz	FFF	[200]
Dipole Antenna/867MHz	MJT	[73]
Dipole Antenna/1GHz	Composite - FFF, ME	[70]
Dipole Antenna/1GHz, 1.8GHz, 2.45Hz, 3.5GHz	Composite - FFF, ME	[201]
Half-wave dipole Antenna/2.2GHz	MJT	[202]
Horn Antenna/100GHz	Composite - FFF, Traditional plating	[117]
Horn Antenna/15GHz	PBF	[203]
Electrically Small Antenna/1.7GHz	ME	[204]
Spherically small Helix Antenna/750MHz	Composite - FFF, Traditional hand painting	[135]
Dielectric Reflectarray Antenna/100GHz	SLA	[113]
Phase Array Antenna	Proprietary Aerosol	[190]
T-Slot Antenna/5.8GHz	Composite - Proprietary Aerosol, FFF	[190]
Inverted-F Antenna/2.4GHz	Composite - FFF, ME	[23]
Vivaldi Antenna/14GHz	Composite - SLA, Traditional plating	[205]
Helical Antenna/8.8GHz	Composite - SLA, MJT	[83]
Monopole Antenna/60GHz	Proprietary Aerosol	[72]
Volcano Smoke Antenna/3.2GHz, 12.6GHz	Composite - BJT, Traditional plating	[206]
Periodic Spiral Antenna	Composite - SLA, Traditional plating	[153]
Conical Spiral Antenna	Composite - FFF, ME	[207]
RFID Antenna	MJT	[73]
Coil Antenna/13.56MHz	MJT	[73]

TABLE 10. Summarization of waveguide types, 3DP technologies and research work for 3D printed waveguides.

Waveguide type	3DP Technology	Reported Work
Antenna Lens 60GHz	FFF	[209]
Luneburg Lens 10GHz	SLA	[210]
GRIN Lens 12GHz	FFF	[211]
Lens 0.1-2THz	SLA	[212]
Lens THz	FFF	[213]
Lens 60GHz	FFF	[209]
GRIN Lens	FFF	[214]
Waveguide (THz)	SLA	[140]
Waveguide Ku-band	Composite - SLA, Traditional plating	[138]
Waveguide 0.2-1.0 THz	SLA	[215]
Vacuum Tube, w-band, 75-110 GHz	SLA	[216]
Frequency selective structure	Composite - FFF, Traditional hand painting	[136]
Frequency selective structure 12.5GHz	Composite - FFF, Traditional plating	[137]
Variant Lattice 15GHz	FFF	[217]
Periodic Surface Lattice 0.1, 0.4, 1.0THz	Composite - SLA, Traditional plating	[218]

G. DIELECTRIC STRUCTURES

For the purpose of the survey, a dielectric structure was considered to be an insulator material which experiences a degree of polarization when an electric field is applied [219]. Dielectric structures represent 7% of the built electrical structures surveyed in the literature. FFF 3DP was the major technology reported in the literature for the implementation of dielectric structures with 54% utilization. The high prevalence of FFF is due, in part, to the ease of combining materials into the printer filament. MJT and SLA printing technologies are the next major 3DP methods with 15% utilization respectively. The use of MJT and SLA can be accounted for by the ability of the processes to produce smooth/high resolution surfaces. EP and Composite techniques constitute the remaining 3DP processes. Table 11 captures examples of the dielectric structure types, 3DP technologies and reported work for dielectric structures.

V. DISCUSSION

In this survey, established 3DP technologies, combination, traditional and proprietary 3DP methods were examined in the context of their utilization for electromagnetic related R&D and electrical end applications. Specific insights were provided into the operation of the 3DP technologies, highlights & issues, the structures built, and materials. From the examination of the reported work there were several cross-cutting challenges which were noted. The first major challenge identified was the inability of a single printing

TABLE 11. Summarization of dielectric structure types, 3DP technologies and research work for 3D printed dielectric structures.

Dielectric type	3DP Technology	Reported Work
Dielectric metamaterial 1.7-2.6GHz	FFF	[220]
Dielectric metamaterial 12-20GHz	FFF	[27]
Dielectric metamaterial 1MHz-10GHz	FFF	[106]
Dielectric metamaterial 15GHz	FFF	[217]
Dielectric metamaterial (wire grid) THz	MJT	[71]
Dielectric substrate 800MHz – 18GHz	FFF	[221]
Dielectric substrate	FFF	[197], [23]
Dielectric substrate	MJT	[44]
Dielectric substrate (magneto-dielectric) 1-6GHz	ME	[222]
Dielectric substrate (magneto-dielectric)	SLA	[223], [224]
Dielectric substrate (ferroelectric-dielectric)	SLA	[81]
Dielectric substrate	Proprietary Aerosol	[190], [72]
Dielectric substrate	PBF	[165]
Microwave dielectric 15MHz	FFF	[225]

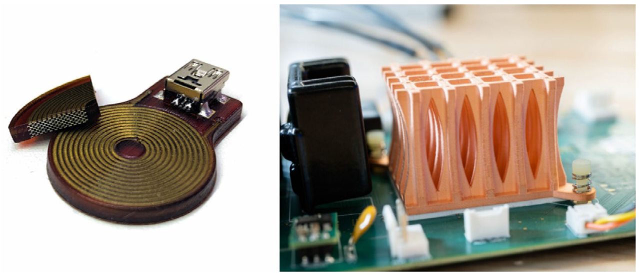

FIGURE 11. Example printed material jetting 3D printed inductor (reproduced with permission from Nano Dimension); example FFF 3D printed copper heatsink (reproduced with permission from Markforged).

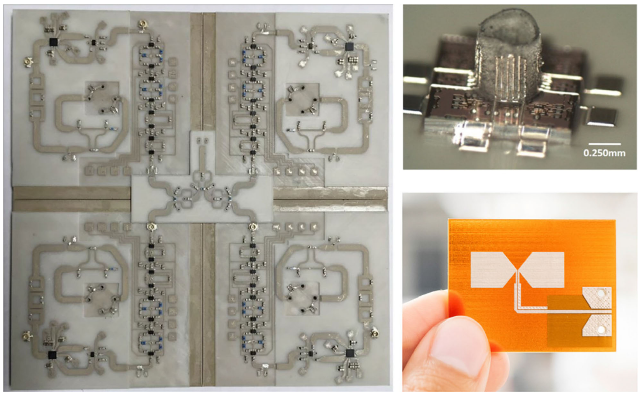

FIGURE 12. Extrusion 3D printed array antenna (reproduced with permission from nScrypt); millimeter wave dipole antenna on a micro structure printed using Aerosol jet 3DP (reproduced with permission from Optomec); material jetting printed bowtie antenna (reproduced with permission from Nano Dimension).

technology to process all of the material categories associated with an electrical structure. A given 3DP technology would demonstrate exemplary processing capabilities with one class of material (e.g. insulative/polymer based) but unsatisfactory or no ability to process other material classes (e.g. conductive/metallic based). Also, for a given 3DP process and its ideal printing material, no 3DP technology was able to embody all of the desirable printing characteristics which would include: printing speed, accuracy, safety, part strength (short and long term), consistency and cost. For example, a 3DP process which is able to provide good print resolution may also demonstrate slow print speeds, user safety challenges due to material toxicity, high cost and/or poor part strength with aging. The aforementioned challenges of wholistic material compatibility and ideal technology characteristics have driven the advent of the 3DP combinations as well as the proprietary 3DP platforms. Noted combinations include EP and FFF/SLA, MJT/Aerosol and FFF/SLA and wire embedding and FFF/SLA. These 3DP combination techniques have been shown to have their own issues of process compatibility, additional processing times required when switching between processes as well as the possibility of contamination during production steps. There is also an added layer of complexity and cost introduced in the 3DP combination solutions. The proprietary 3DP technologies presented in the literature represent a significant upfront cost and cost of operation (materials, trained staff and expendables). The proprietary solutions are also very specific as relates to their application focus (e.g. precision jetting of conductive materials).

Overall, there is still ongoing developments across all 3DP technologies in the areas of materials, equipment and processes with many opportunities for research. In the area of 3DP materials, owing to the wide array of processes and the ongoing development of additional materials, there exists a significant need for the characterization of the mechanical, electromagnetic and thermal properties of these materials. In particular, the areas of electromagnetic and thermal characterization represent a significant gap in the research. Another opportunity for 3DP material studies lies in the area of material aging. There exists a significant gap in characterizing the changes in the mechanical, thermal and electrical properties of the 3DP materials due to aging under various conditions (sunlight, heat, moisture, corrosion). The need for characterization and understanding the variations of aging can be further extended beyond single materials to consider multimaterials as well as material combinations which are evident in any functional electrical structure (e.g. dielectric and metallic material combinations). The area of

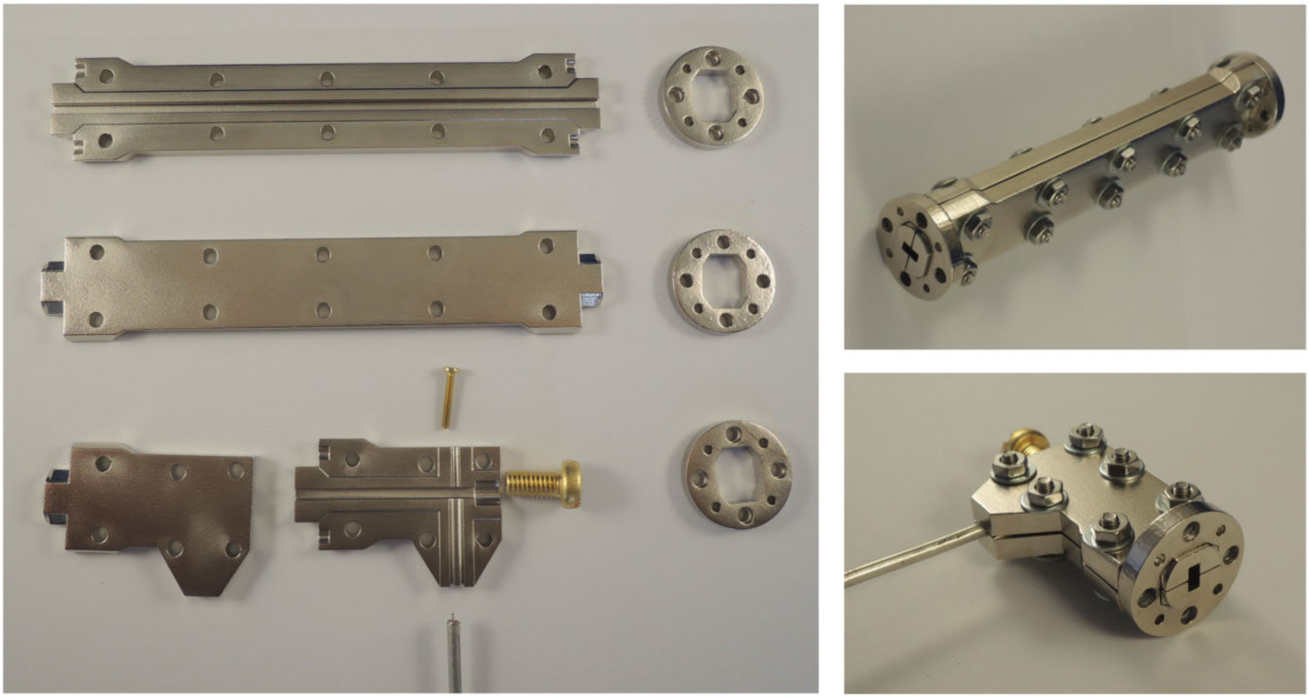

FIGURE 13. Example WR15 plastic waveguide produced using SLA 3DP and finished using Ni-Ci electrochemical plating (reproduced with permission from ALCIOM).

multimaterials (binary, ternary) represents a key area for ongoing research as relates to the resultant characteristics of the built structures. Thus, one can conclude that there exist many opportunities for ongoing research and development into equipment, materials and process improvements.

The wide variety of electrical and electromagnetic 3D printed structures highlighted in this survey is indicative of the continued interest in applying 3DP technologies to EM related applications. The examination of the literature was able to identify seven (7) categories of electrical structures. Antennae and sensors represent two well established categories where 3DP technologies are applied to manufacture end use solutions. The authors anticipate that the utilization of 3DP to these two areas will continue to mature with dedicated processes, materials and equipment. However, there is still room for the development and integration of software tools for the design and modeling of antennae and sensor structures which are intended to be manufactured using these 3DP technologies. The literature also highlighted the maturity of 3DP technologies as applied to waveguides. The need for quality metallization of the waveguide structures (particularly for RF and microwave frequencies) can be expected to be an ongoing area for further work. Finally, the realization of a complete 3D printed complex electrical system continues to be an area of significant interests.

This survey has highlighted many researchers and commercial initiatives which have offered various hybrid solutions to the complete production of an electrical system. It is important to note that these solutions as discussed in this survey involve the integration of discrete electronic components (integrated circuits, passive components) which have been manufactured using well established traditional methods of electronics manufacturing. Therefore, the production of a fully 3DP complex electrical system (inclusive of electronics components and other elements) is yet to be realized. This survey has highlighted several separate instances of reported work in the area of passive components. There is opportunity for further work into the design of passive components and other discrete devices which can supplant the use of traditional discrete electronic components to realize a fully 3DP solution. In closing, the authors believe that the impact of the COVID-19 pandemic and geopolitical tensions on the electronics manufacturing industries and supply chains will continue to drive interest in the retooling of the electronics (and related) sectors in the aforementioned areas. Therefore, the area of 3DP technologies as applied to electromagnetic related R&D and electrical end applications will continue to present many exciting opportunities for future work.

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