# 3D printing of passive electronic components

# from the perspective of a components manufacturer

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## ABSTRACT

In recent years, the development of passive components has been driven by reliability, performance, new functionality, mass and volume reduction as well as cost reduction. Passive component manufacturing processes subsequently have two main objectives: (1) maintaining high-quality standards and (2) cost efficiency. Looking at the example of multilayer ceramic chip capacitors (MLCC), manufacturing includes processes such as screen printing, stacking, cutting, and sintering. These manufacturing processes are performed at high speed (roll-to-roll, 1 m/s) with a yield of >99% and material waste of less than 2%. This proves that in this industry, additive manufacturing has been a standard for many years. Therefore, to be competitive, state-of-the-art production lines for such components are highly product-specific and always configured for high volumes. These constraints result in long and costly development cycles due to lead times of manufacturing equipment, tooling and infrastructure. In addition, today's production technologies only allow for simple rectangular component shapes. Various manufacturing industries already provide application examples, where the technology of 3D printing enables rapid prototyping, design flexibility, on-demand production, or supply chain independence. Yet, 3D printing of passive electronic components has still not been introduced. However, recent developments in materials and 3D printing technologies could enable a significantly faster time-to-market, low-volume ("batch-size-one"), and application-specific design of components. Aside from maintaining 3D printing equipment, no specific undertakings are needed for holistic design, advanced construction, and fast manufacturing of the desired products. Thus, the manufacturing of low-volume advanced electronic components takes a huge leap forward with 3D printing. This research explores gaps and opportunities for 3D printing in the context of electronic components manufacturing from the perspective of a passive electronic components manufacturer.

## INTRODUCTION

Electronic components represent the fundamental building blocks of modern electronics, forming the core of a vast array of devices, from smartphones, computers, medical devices, to spacecrafts. In recent decades, their miniaturization, performance, and reliability steadily increased, enabling the development of ever-more sophisticated and compact electronic devices. Directly related to the advancement of passive electronic components are ceramics as material and the related advancements in its processing technologies [1].
This paper explores gaps and opportunities for 3D printing in the context of electronic component manufacturing from the perspective of an electronic components manufacturer focusing on passive components based on electro-ceramic materials.

## CERAMIC-BASED PASSIVE COMPONENTS, ITS STATE-OF-THE-ART MANUFACTURING PROCESS, AND MARKET TRENDS

According to [2], ceramic materials offer several beneficial characteristics that make them suitable for electronic devices like high thermal conductivity, mechanical strength, chemical stability, and high resistance to electronic conduction. In addition, certain ceramic materials enable specific and distinct electronic products as the material defines the major

properties of the final product in electro-ceramics. Examples are dielectric ceramics (capacitors) or piezoelectric ceramics (e.g., transducers, sensors, vibrators) [2].
One of the most common applications of ceramics in passive components is Multi-Layer Ceramic Capacitors (MLCC) [1]. This section provides a brief overview of state-of-the-art manufacturing processes, market trends, and major advancements of MLCCs to date to give an insight into the business of a passive component manufacturer.
[3] summarizes the manufacturing process as follows (see Figure 1 [4]). The manufacturing process of MLCCs encompasses a series of pivotal stages, commencing with the selection of raw materials. These materials typically include ceramic powders, metal electrodes, and a variety of additives that are included to enable zero-defect manufacturing as well as enhance the overall performance of the finished product. The initial stage of the MLCC manufacturing process entails the preparation of ceramic slurry, which is a combination of ceramic powders and binders. Subsequently, the slurry is cast into thin layers and dried, thereby forming ceramic tapes. Subsequently, metal electrodes are printed onto the aforementioned tapes via a screen-printing process. Thereafter, multiple layers of ceramic tapes with electrodes are stacked together to form a multilayer structure. The next crucial step is the multiple thermal processing of the multilayer ceramic green bodies. This typically comprises at least a de-binding and a sintering process, whereby the stacked layers are heated at high temperatures to bond them together. This process helps to create a solid ceramic body with well-defined internal electrode layers. After sintering, the MLCCs undergo additional processes such as laser trimming, coating, and testing to ensure quality and reliability [3].

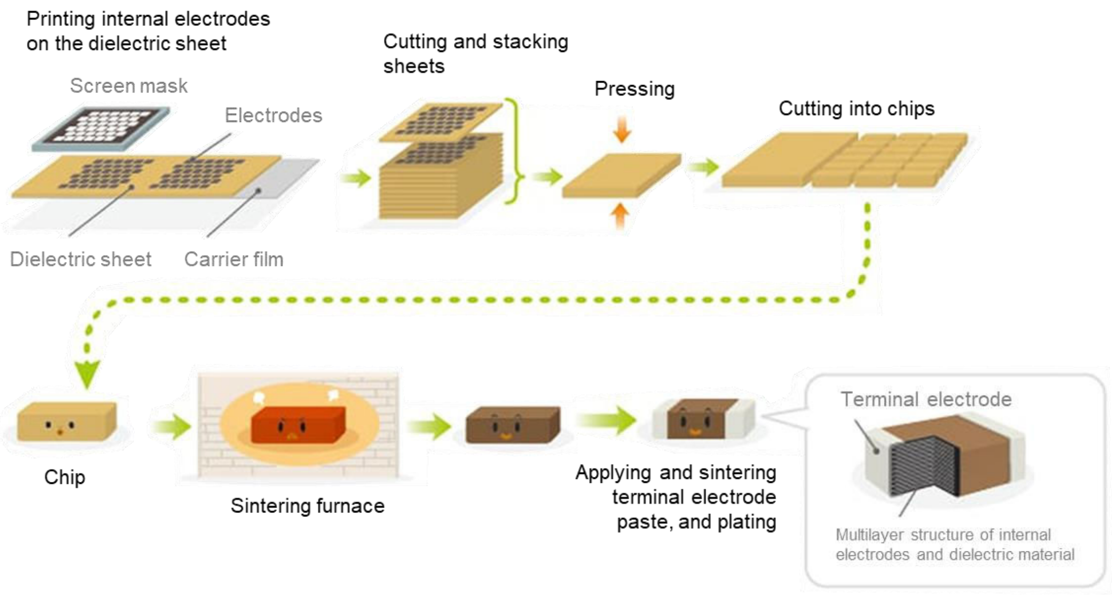


Figure 1: Manufacturing process of multilayer ceramic chip capacitors (MLCC) [4].

Current industry reports show continuing growth of the overall MLCC market with a CAGR (2024 – 2029) of 21.57% reaching an expected market volume of 61.16 billion USD [5]. Further, market trends are amongst others: (1) miniaturization; (2) low-range voltage MLCCs; or (3) high-range capacitance [5].
The fast-paced development and ever-increasing requirements for MLCCs in combination with price pressure on the markets [5] show the importance of efficient production processes.
Reference [3] highlights the complexity and required competencies for passive component manufacturers:

"*The economical mass production of high quality, reliable and low-cost multilayer ceramic (MLC) capacitors requires a thorough understanding of the characteristics of the materials used, a knowledge of chemistry and electronics, as well as a high level of expertise in mechanical-equipment design and in-process technology*." [3]

**Limitations of ceramic passive electronic components manufacturing**

These manufacturing processes typically come with narrow process windows and their own set of limitations that can iinfluence yield, design flexibility, and long-term reliability.

These limitations are:

- **Product-specific lines:** In contrast to some integrated circuits, MLCC production lines are frequently explicitly dedicated to a specific product type due to the complex interplay of materials and firing profiles. This results in reduced flexibility and higher production costs for small batches and customer-specific products [6].
- **Tooling constraints:** As MLCCs continue to decrease in size, the production of electrodes and manipulation of dielectric layers become increasingly challenging. The current tooling methods may not be adequate for complex geometries beyond the basic cuboid shape, impeding advancements in miniaturization efforts [7].
- **Development cycles:** New developments generally start with extensive material research and involve all the following process steps. For example, sintering as stand-alone process requires meticulous control of atmosphere and temperature. Deviations can lead to compositional changes, oxidation, and ultimately, compromised performance and reliability [7]. This leads to lengthy development cycles for new MLCC generations.

As summarized in [7], multi-material 3D printing offers the potential to re-think functional ceramic design. Unlike traditional methods, it allows for the rapid creation of complex parts with diverse materials, eliminating the need for costly tooling.

## 3D PRINTING: POTENTIAL, CHALLENGES, AND APPLICATION EXAMPLES

Since the 1980s, 3D printing has revolutionized manufacturing by enabling the creation of complex objects directly from digital models, one layer at a time. This transformative technology encompasses seven distinct subcategories: (1) material extrusion (e.g., filament printing); (2) material jetting (e.g., inkjet printing); (3) binder jetting (printing with a binding agent); (4) vat photopolymerization (using light to cure liquid resin); (5) powder bed fusion (melting or sintering powder); (6) direct energy deposition (melting material with a laser); and (7) sheet object lamination (bonding pre-made sheets) [8].

### 3D printing technologies for ceramic structures

[9] summarizes ceramic 3D printing technologies (see overview in Table 1). This research does not aim to explain the specifics of different technologies in detail.

Table 1: Ceramic 3D printing technologies (adapted from [9]).

| Feedstock form | Ceramic 3D printing technology | | Feedstock form | Ceramic 3D printing technology |
|---|---|---|---|---|
| Slurry-based | Stereolithography | | Powder-based | Three-dimensional printing |
| | Digital light processing | | | Selective laser sintering |
| | Two-photon polymerization | | | Selective laser melting |
| | Inkjet printing | | | |
| | Direct ink writing | | Bulk solid-based | Fused deposition modelling |

### Multi-material 3D printing of functional ceramic components

Functional ceramic devices are distinguished from structural ceramics by their ability to detect, transform, couple, transmit, process, or store information. This information can be in the form of electrical signals, magnetic fields, or light [10].

As explained in [11], it should be noted that functional ceramic devices usually consist of two or more materials and contain structures like strip lines and vias. Pertaining to 3D printing, this results in several challenges involving raw material (e.g. sintering) and printing strategies (e.g. avoiding cross-contamination). However, in a review study [11] presents exemplary projects related to fused deposition modeling, material jetting, and vat-photopolymerization-based technologies and discusses respective advantages and challenges (see Table 2). It is concluded that multi-material 3D printing is still in an early development phase [10].

Table 2: Suitability of printing technologies for manufacturing functional ceramic components (based on [11]).

| Printing technology | Advantages | Challenges |
|---|---|---|
| Fused deposition modelling | - Implementation<br>- Cost | - Surface finish<br>printing resolution |
| Direct ink writing | - Material adaptability | - Throughput |
| Material jetting | - Printing resolution | - Material formulation |
| Vat photopolymerization based | - Surface finish<br>- Resolution<br>- Throughput | - Multi-material capabilities |

Reference [13] reports three main factors limiting the scalability of 3D printing of electronic components in general: (1) slow printing speed; (2) mismatch of material properties; and (3) pre- and post-processing. Furthermore, in line with [13], the authors highlight the need for advances in multi-material 3D printing to realize integrated electronic devices. Current limitations in printing a variety of materials simultaneously restrict the fabrication potential of 3D printing in this field. Future developments in multi-material printing will be crucial to enable the single-step creation of integrated electronics [11].

As illustrated in Table 2, vat-photopolymerization-based technologies offer capabilities for 3D printing ceramic electronic components, particularly in terms of resolution and throughput. Despite the general limitations of its multi-material 3D printing capabilities stated by [12], recent advancements have demonstrated the potential for enabling such 3D printing through the development of first products (e.g., [13]) and ongoing research and development activities in the 3D printers themselves (e.g., [14]) as well as in the combination of different printing and structuring techniques (e.g., [15]).

**Selected application examples**

In [11], the authors present various fundamental electronic components manufactured using 3D printing technologies. Examples are e.g. capacitors, resistors, inductors, or antennas [16].
However, from the perspective of an electronic component manufacturer, it is not economically feasible to produce 'classic' passive components using 3D printing technology due to its limitations, which result in higher costs compared to today's standard, high-volume manufacturing lines.
Looking at other industries, aviation in particular is considered as one of the most advanced industries using 3D printing. Not only for rapid prototyping, but to manufacture complex parts that cannot be manufactured using any other technology e.g. General Electric Aviation successfully produced 30,000 Metal 3D printed fuel nozzle tips in 2018. This achievement was possible due to the design freedom of 3D printing leading to a reduced number of parts in the fuel nozzle from 20 to 1 and, in parallel, cutting the weight by 25% [17].

Similar success stories in different industries lead to the conclusion that finding the right application for 3D printing in the sector of electronic components is as crucial as the continued development of printing technologies themselves. The question remains: "Where can 3D printing provide a similar value to the electronic component business as the fuel nozzle did for GE Aviation?"

**Where 3D printing could make sense**

In the following, the authors of this research claim two hypotheses where 3D printing of ceramic-based electronic components can provide additional value justifying higher costs (except prototyping applications). Further, this paper introduces selected examples of such 3D printed, prototypical components using a vat-photopolymerization-based technology (digital light processing) citing unpublished, pending patent [18] and utility model [19] applications.

As introduced, as limitations of the state-of-the-art manufacturing processes for MLCCs, the current tooling methods may not be adequate for complex geometries beyond the basic cuboid shape. This leads to hypothesis one: *"3D printing enables the production of free-form components that are not subject to the design or shape conventions of classic ceramic production"*.
Furthermore, today's standard in electronics is that prefabricated electronic components are connected, for instance via printed circuit boards or other connecting means ("like LEGO® bricks"). However, the individually prefabricated electronic components assembled in such a modular system do not contribute to the formation of a structure or perform structural functions. Instead, they frequently require additional structural functions to protect them from external influences. This leads to hypothesis two: *"Multi-material 3D printing enables the combination of structural strength, shielding, heat management and/or electrical insulation (ceramic) and active functions (e.g. copper, piezo actuators, temperature sensors) resulting in a higher integration of functional components"*.

Example one of such a 3D printed component is a microfluidic device with microchannels for inflow and outflow, a reaction chamber and integrated heating functions. The structural element including the channels and the reaction chamber is made of ceramic. The heating functions are realized using a resistance heater made of copper. Either all elements (inflow, outflow, and reaction chamber) or the reaction chamber itself can be heated specifically. The material properties of the ceramic (temperature resistance, chemical resistance), the free-form capability of 3D printing (internal micro-channels), and the possibility of heating 'on the spot' using multi-material 3D printing might create additional value for future flow chemistry applications (see Figure 2 [18]).

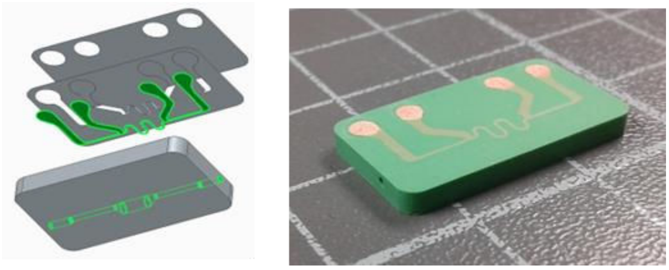

Figure 2: Example of a 3D printed, integrated microfluidic device (materials: ceramic, copper) [18].

A further application of multi-material 3D printing of ceramic-based electronic components is a (hermetic) package. The package itself is designed for a MEMS application including the necessity of placing a cover on a tilted ring to package a MEMS device. The package design is enabled by free-form capabilities of 3D printing (tilted ring, cavity), and multi-material 3D printing (conductive copper traces/pads). Further potential of 3D printing is e.g. including microchannels into the substrate for active cooling. Another advantage of using 3D printing is the comparably fast time from 'digital model (CAD) to real product' within 2 weeks, whereas heat treatment (debinding & sintering) is the limiting process step. Figure 3 shows the 3D-printed ceramic package including conductive copper traces and pads [18] & the assembled, sealed 3D-printed ceramic package with glass cover, electronic units and a MEMS device inside [19].

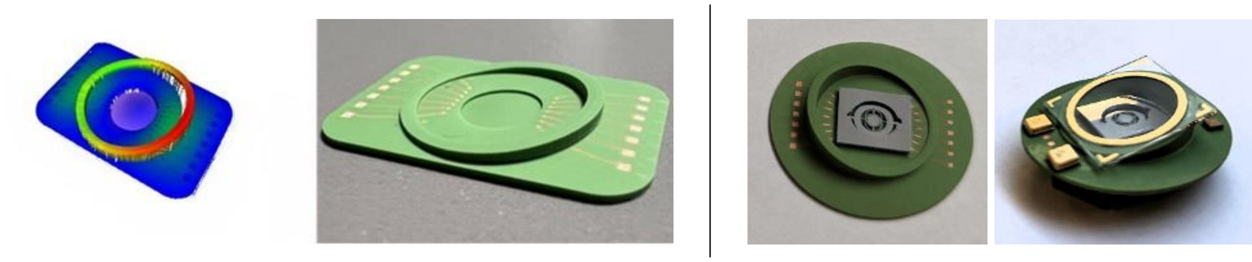

Figure 3: Example of a 3D printed package (materials: ceramic, copper) [18] – left – and assembled and sealed 3D-printed package with a MEMS device inside the cavity [19] – right.

## CONCLUSION

The current state-of-the-art manufacturing of passive electronic components relies on well-established yet inflexible processes. While these processes deliver high-volume production at a competitive cost, they struggle with limitations in design freedom and customization.

3D printing technology offers a glimpse into the future of electronics manufacturing, particularly with advancements in multi-material printing. This technology has the potential to overcome the limitations of traditional methods by enabling the production of: (1) free-form components with complex geometries beyond the basic shapes achievable with current tooling methods; (2) highly integrated functional components that combine structural strength (ceramics) with active functions (conductors, sensors) within a single component. The authors showed two potential future applications in which 3D printing has the potential to create added value from previously unmanufacturable components that exceeds the associated costs.

Despite first prototypical applications, 3D printing remains in its early stages for electronic component manufacturing. Challenges include printing speed, material properties that match traditional methods, and the need for further development in multi-material printing.

From the viewpoint of a component manufacturer, 3D printing will not substitute proven production technologies for electronic components. However, the true value of 3D printing might be in "form follows function" applications or in the integration of functions ("from components to systems") for high-performance markets or where fast time-to-market is crucial.

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