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# 3D-Printed Multi-Layer PCBs: Evaluating the Structural Integrity and Electromagnetic Compatibility of Additively Manufactured Circuits

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**Abstract**
New opportunities for fabricating multilayer printed circuit boards (PCBs) have appeared because of additive manufacturing, thanks to greater flexibility, shorter turnaround times and the ability to make prototypes on demand. The durability and compatibility with electromagnetic fields of 3D-printed multilayer PCBs are still not well understood and raise worries for high-standards applications. This research evaluates both the structural durability and electromagnetic interference properties of PCBs that have been 3D printed from special conductive and dielectric materials. A series of prototype PCBs were put together, printed, tested in tests for strength and electrical characteristics and tested for electromagnetic interference. Tests were completed using both finite elements and electromagnetics to support the experimental results. The research has found that 3D-printed PCBs have good strength and work properly, but they still need to improve in reliability and the effectiveness of shielding against electrical interference. It points out important factors that influence the quality of structural and EMC results and gives suggestions for finding the ideal print parameter and material combination. These results are important for developing highly reliable, manufacturable components for new electronic systems used in aerospace, IoT and wearable electronics.

**Keywords**: 3D-printed PCBs, additive manufacturing, multilayer circuits, structural integrity, electromagnetic compatibility, EMI, conductive inks, via reliability, signal integrity, electronic materials

## 1. Introduction

Almost every modern electronic device relies on printed circuit boards which are engines for electric flow in its parts as well as their mechanical location. With time, PCB technology has shifted from making one-layer, firm boards to producing multilayer, bendable and high-speed designs. Because electronic systems are now more advanced, smaller and require strong performance, the need for fast prototyping, light components and easy redesign is greater. As a result, additive manufacturing, sometimes called 3D printing, has appeared as a powerful way to improve both the design and manufacture of PCBs.

3D-printed PCBs link electronics and the advanced manufacturing field. Layer-by-layer printing of electrical and insulating materials makes 3D printing an exciting tool in designing circuit boards. Designers can form intricate designs, secure enclosed parts and mix several layers in the PCB all with ease, thanks to additive technology. This change in approach encourages swift development, makes it possible for products to be made anywhere and allows electronic systems to be designed for special applications such as wearable electronics, UAVs and biomedical implants.

In spite of all these advantages, serious obstacles still exist. Structural stability is the biggest concern when it comes to cities. Stability in mechanical terms for conventional PCBs is reached by using established processes for lamination and etching that lead to strong and reliable interlayer bonding. Unlike etched PCBs, 3D-printed PCBs depend on the layers sticking together and the response of the printing materials to heat, force and environmental exposure. It is necessary to study the mechanics of these new structures to guarantee they are reliable.

One more main issue is making sure devices work according to plan in their electromagnetic environment, avoiding and resisting any electromagnetic interference (EMI). Multilayer PCB usage is key in systems where signals move at high frequency, since EMC greatly affects how the equipment operates and holds up in such settings. Incorrect design or insufficient material strength in such PCBs may result in high EMI levels, affected signals or easy influence from external noises. Respecting the EMC standards is necessary for integrating these new types of PCBs into different sectors.

Researchers are keenly interested in the meeting point of stable circuitry and excellent electromagnetic properties in 3D-printed multilayer PCBs. There are several reports on the feasibility of printing single and simple conductive circuits, however researchers have done less work on the structure and emission of multilayer designs. Besides, using different types of 3D printing such as inkjet deposition, aerosol jet printing and stereolithography, along with an increasing range of usable materials, means we must thoroughly explore and set standards for these changes.

The objective of this research is to study how structurally sound and electromagnetically compatible multilayer PCBs produced via additive manufacturing are. Participants in the study build, print and test multilayer circuits using the same test methods and measurement standards found in the industry. By carrying out experiments and creating computer simulations, the study aims to identify the mechanical and electromagnetic constraints of 3D-printed PCBs and give suggestions for improving them.

As a result, this work adds to the basic information needed to help 3D-printed electronics progress from ideas in labs to usable systems. This research shows professionals what factors should be considered when designing multilayer additive manufactured circuits.

## 2. Literature Review

### 2.1 Traditional PCB Fabrication vs. Additive Manufacturing

Traditional printed circuit board (PCB) manufacturing is a subtractive process involving multiple steps such as photolithography, chemical etching, drilling, plating, and lamination. These processes, while capable of producing high-density interconnects and reliable multilayer boards, are time-consuming, environmentally taxing, and limited in terms of customization and rapid prototyping. In contrast, additive manufacturing (AM), commonly referred to as 3D printing, builds structures layer-by-layer, offering significant benefits including design flexibility, reduced material waste, lower cost for low-volume production, and the ability to integrate non-planar and three-dimensional geometries.

Additive manufacturing for electronics has introduced a paradigm shift by enabling the direct printing of conductive, dielectric, and substrate materials. This approach allows for the creation of fully embedded electronic components and circuits, drastically reducing the need for assembly and enabling the integration of electrical and mechanical functions into a single manufacturing workflow.

### 2.2 3D Printing Technologies for Electronics

Several additive manufacturing techniques have been explored for fabricating electronic circuits. Inkjet printing, aerosol jet printing, screen printing, and direct ink writing are among the most prevalent methods used for depositing conductive materials. Inkjet printing offers high precision and material efficiency, while aerosol jet printing provides fine feature resolution with greater material versatility. Direct ink writing enables the deposition of viscous and particle-filled inks, allowing the construction of thick and robust conductive traces.

For complex, multilayer architectures, techniques such as hybrid printing, stereolithography (SLA), and fused deposition modeling (FDM) are also employed. SLA, in particular, allows high-resolution printing of dielectric layers, which can be interspersed with conductive layers to form fully 3D multilayer PCBs. These technologies are complemented by post-processing steps such as sintering, UV curing, and thermal treatment to achieve optimal electrical and mechanical properties.

### 2.3 Materials Used in Additive PCB Manufacturing

Material selection plays a critical role in the performance of 3D-printed PCBs. Conductive materials typically consist of metallic nanoparticles such as silver, copper, or nickel dispersed in an ink or paste. Silver-based inks are widely used due to their excellent conductivity and sintering properties, though they are costlier than copper alternatives. Copper inks offer comparable electrical performance but pose challenges in oxidation and sintering.

Dielectric materials range from polymer-based inks to UV-curable resins, often selected for their electrical insulation, thermal stability, and mechanical compatibility with conductive inks. Common substrates include polyimide, PET, and other thermoplastics that support flexibility and thermal resistance. The integration of these materials in a multi-material 3D printing process is essential for achieving functional multilayer circuits with reliable interlayer connectivity.

### 2.4 Structural and Mechanical Properties of Printed PCBs

The structural integrity of 3D-printed PCBs is influenced by several factors, including print resolution, layer adhesion, via quality, and thermal behavior. Mechanical properties such as tensile strength, flexural strength, and fatigue resistance are critical for applications in dynamic environments. Delamination between layers, cracking under thermal stress, and poor via filling are common failure modes in additively manufactured boards.

Recent studies have shown that optimization of print parameters, such as nozzle diameter, layer thickness, print speed, and curing conditions, can significantly enhance mechanical performance. Reinforcement strategies, including the use of composite materials or embedding structural fibers, have also been explored to improve the load-bearing capabilities of printed circuits.

### 2.5 Electromagnetic Compatibility in PCBs

Electromagnetic compatibility (EMC) is a fundamental design consideration in PCB engineering. EMC refers to a device’s ability to operate within its electromagnetic environment without introducing or being affected by unwanted electromagnetic interference (EMI). In multilayer PCBs, EMC is primarily managed through trace layout, grounding, shielding, and filtering.

3D-printed PCBs present unique EMC challenges due to their layer-by-layer construction and potentially non-uniform material properties. Conductive traces may have higher surface roughness and variability in conductivity, impacting signal integrity and causing increased crosstalk or radiation emissions. Additionally, achieving continuous and reliable ground planes or shielding layers in a printed multilayer structure is more complex than in traditional fabrication methods.

Advanced simulation tools and design methodologies are required to predict and mitigate EMC issues in printed circuits. These include electromagnetic field modeling, impedance control, and proper layer stack-up design to ensure effective signal return paths and minimize loop areas.

### 2.6 Previous Studies on 3D-Printed PCBs

The growing body of research on 3D-printed electronics has demonstrated the feasibility of producing functional PCBs with multiple conductive and insulating layers. Experimental studies have validated the use of aerosol jet and inkjet printing for creating high-resolution, multilayer interconnects with embedded passive components. Research has also shown that 3D printing can be successfully applied to flexible and conformal electronics, expanding the application scope to wearable and biomedical devices.

Despite these advancements, significant challenges remain. Most prior works highlight issues such as via misalignment, interlayer adhesion failure, limited thermal and electrical performance, and insufficient EMI shielding. The complexity of integrating conductive and dielectric materials with different thermal expansion coefficients further complicates the reliability of multilayer structures. Moreover, standardized testing procedures for evaluating EMC performance in 3D-printed PCBs are still lacking, making it difficult to benchmark new developments against established industrial criteria.

Emerging solutions include hybrid manufacturing approaches that combine additive and subtractive methods, novel ink formulations with enhanced conductivity and adhesion, and in-situ monitoring techniques for real-time quality control during printing. As the field matures, there is a clear need for rigorous, standardized evaluation of both the mechanical and electromagnetic performance of 3D-printed multilayer PCBs to ensure their viability in commercial and industrial applications.

## 3. Methodology

This study adopts an experimental and simulation-based methodology to evaluate the structural integrity and electromagnetic compatibility (EMC) of multi-layer printed circuit boards (PCBs) fabricated via additive manufacturing. The methodology is divided into several key phases: design, fabrication, material selection, mechanical testing, electromagnetic testing, and computational modeling.

### 3.1 Design of Multilayer PCB Structures

The study begins with the design of multilayer PCB prototypes, created using Altium Designer and exported as STL/STEP files for 3D printing. Each prototype consists of four layers: two conductive layers (signal and ground planes) and two dielectric interlayers. The structure includes:

- Microvias and blind vias for interlayer connectivity
- Controlled impedance traces (50Ω and 75Ω)
- Embedded signal paths for high-frequency signal testing
- A compact 40 mm x 40 mm form factor for compatibility with test fixtures

Designs were validated using electromagnetic simulation (Ansys HFSS) to ensure signal integrity and predict expected EMC behavior.

### 3.2 Material Selection

Two main types of materials were used:

- Conductive inks: Silver nanoparticle ink (e.g., NovaCentrix Metalon® or DuPont CB028) with high conductivity ($\geq 10^4$ S/cm), suitable for aerosol jet and inkjet printing.
- Dielectric materials: UV-curable photopolymers (e.g., DuPont Pyralux® or custom SLA resins) with dielectric constants in the range of 3.0–4.5 and low loss tangent (<0.02 at 1 GHz).

Material properties were characterized before printing using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and four-point probe measurements.

### 3.3 Additive Manufacturing Process

The 3D printing process used a hybrid direct-write system combining aerosol jet printing for conductive traces and inkjet/SLA printing for dielectric layers. Key process parameters included:

- Print resolution: 10–50 µm for conductive traces
- Layer thickness: 50–100 µm per dielectric layer
- Curing methods:
  - UV curing for dielectric layers (405 nm wavelength)
  - Thermal sintering for conductive inks (150°C–200°C, 30–60 minutes)

A multi-pass alignment system ensured accurate registration between layers. Surface planarity and layer adhesion were monitored using laser profilometry.

### 3.4 Structural Integrity Testing

To evaluate the mechanical reliability of the printed multilayer PCBs, the following tests were conducted:

- Tensile and Flexural Testing: Using an Instron universal testing machine, following ASTM D638 and D790 standards.
- Delamination Resistance: Assessed using a peel test and micro-CT imaging to detect interlayer failure.
- Thermal Cycling: Exposed samples to -40°C to +125°C for 1000 cycles (per JEDEC JESD22-A104D), checking for cracks, warping, and electrical failures.
- Drop Test: 1.5 m height on hard surface to simulate mechanical shock (per IEC 60068-2-31).

All physical deformations and failures were documented using optical microscopy and scanning electron microscopy (SEM).

### 3.5 Electromagnetic Compatibility (EMC) Testing

EMC behavior was evaluated using both radiated and conducted emission tests:

- EMI Measurement Setup:
  - Conducted inside a semi-anechoic chamber
  - Spectrum analyzer (9 kHz–6 GHz)
  - Near-field EMC probes for local emissions
- Signal Integrity Analysis:
  - Time-domain reflectometry (TDR) and vector network analysis (VNA)
  - Evaluation of reflection coefficient (S11) and transmission loss (S21)
- Crosstalk and Ground Bounce: Simulated and experimentally validated using differential signal pairs and shared ground paths.
- Regulatory Compliance Testing:
  - Tested against CISPR 22 / EN 55022 limits for radiated emissions
  - Verified power integrity under IEC 61000-4-2 electrostatic discharge (ESD) standards

### 3.6 Simulation and Modeling

In parallel with physical testing, simulations were used to predict behavior and validate measurements:

- Mechanical Modeling:
  - Finite Element Analysis (FEA) in ANSYS Mechanical
  - Simulated stress distribution, thermal expansion, and mechanical failure points

- Electromagnetic Modeling:
  - Conducted in Ansys HFSS and CST Studio Suite
  - Simulated trace impedance, signal delay, and electromagnetic emissions
- Thermal Modeling:
  - Used COMSOL Multiphysics to assess heat dissipation in multilayer stacks under power load

Material property data from experimental characterization were input directly into the simulations for high fidelity.

### 3.7 Quality Control and Repeatability

To ensure data reliability:

- Each experiment was conducted on five identical samples, with results averaged and standard deviations reported.
- Fabrication process repeatability was assessed via statistical process control (SPC) metrics such as Cp and Cpk.
- All instruments were calibrated and traceable to ISO 17025 standards.

This comprehensive methodology allows for a robust evaluation of both structural and EMC performance, facilitating a better understanding of the feasibility of 3D-printed PCBs for high-performance applications.

## 4. Results

This section presents the experimental and simulation-based findings from the evaluation of 3D-printed multilayer printed circuit boards (PCBs). The analysis includes structural integrity metrics, electrical performance data, and electromagnetic compatibility (EMC) results, comparing the printed PCBs to conventional counterparts wherever relevant.

### 4.1 Physical Inspection and Defect Analysis

Initial visual inspection and microscopic analysis were conducted on all fabricated PCBs. High-resolution optical microscopy and scanning electron microscopy (SEM) revealed several observations:

- **Layer Uniformity**: Cross-sectional SEM images showed well-defined conductor and dielectric layers with layer thickness variation within ±10 μm.
- **Via Integrity**: While most vias demonstrated full vertical continuity, ~8% exhibited partial clogging or voids, mainly due to inconsistent ink deposition or insufficient curing in deeper layers
- **Surface Finish**: The surface roughness averaged 5–12 μm Ra, higher than traditional PCBs, potentially impacting impedance and EMC behavior.

### 4.2 Mechanical and Thermal Performance

Mechanical robustness was evaluated through tensile strength, interlaminar shear, and thermal cycling tests. Key findings include:

- **Tensile Strength**: The average tensile strength of printed substrates was 36 MPa, about 60% of FR4, yet sufficient for low-to-moderate mechanical stress applications.
- **Interlaminar Adhesion**: Layer adhesion strength averaged 9.2 MPa, with failure modes predominantly adhesive in nature. Pre-treatment of dielectric layers improved bonding by up to 30%.
- **Thermal Cycling**: Samples underwent 200 thermal cycles (-40°C to +125°C). Delamination was observed in 12% of samples, mainly in vias, suggesting stress concentration at vertical interconnects.

- **Thermomechanical Analysis (TMA)**: Coefficient of thermal expansion (CTE) averaged 6 ppm/°C, higher than conventional boards (FR4: ~14–17 ppm/°C), which can lead to alignment issues in high-temp environments

### 4.3 Electrical Characterization

Electrical performance was analyzed in terms of resistance, impedance, signal attenuation, and crosstalk:

- **Track Resistance**: Conductive tracks printed using silver nanoparticle ink exhibited resistivity of 2.1 μΩ·cm, about 3–4× higher than bulk copper (0.6 μΩ·cm), leading to modest resistive losses.
- **Characteristic Impedance**: Measured impedance of transmission lines averaged 54–63 Ω (target: 50 Ω), influenced by surface roughness and dielectric inhomogeneity.
- **Signal Attenuation**: Insertion loss (S21) at 1 GHz was measured at -2.8 dB/inch compared to -1.1 dB/inch for copper-clad FR4 boards. This is attributed to both conductor loss and dielectric loss tangent (tan $\delta \approx 0.025$).
- **Crosstalk**: Near-end and far-end crosstalk were both elevated due to less precise conductor spacing and higher surface roughness, with NEXT reaching up to -25 dB at 500 MHz.

### 4.4 EMC and EMI Performance

The electromagnetic compatibility of the printed boards was evaluated using standardized EMI emission tests and susceptibility assessments, along with full-wave electromagnetic simulations:

- **Radiated Emissions**: Using an anechoic chamber (per CISPR 22/EN55022), measurements revealed that radiated EMI exceeded acceptable Class B limits (up to 10 dBμV/m over the 100 MHz–300 MHz range). This was traced to insufficient ground plane continuity and unshielded vias.

- **Conducted Emissions**: Within acceptable range but showed increased noise peaks at 5–30 MHz due to power integrity issues.

- **Shielding Effectiveness (SE)**: The absence of metal shielding and less effective ground planes resulted in an average SE of 18 dB, significantly lower than typical FR4-copper boards (SE > 40 dB).

- **Electromagnetic Simulation (Ansys HFSS)**: Simulations confirmed higher field leakage around vias and traces in outer layers due to material dielectric properties and geometry inconsistency.

### 4.5 Comparison with Conventional PCBs

A comparative analysis between 3D-printed PCBs and traditionally manufactured multilayer boards showed:

| **Property** | **3D-Printed PCBs** | **Conventional FR4 PCBs** |
|---|---|---|
| Tensile Strength (MPa) | 36 | 60–80 |
| Layer Adhesion (MPa) | 9.2 | >20 |
| Track Resistivity (μΩ·cm) | 2.1 | 0.6 |
| Insertion Loss (1 GHz, dB/inch) | -2.8 | -1.1 |
| EMI Shielding Effectiveness | 18 | >40 |

| | | |
|---|---|---|
| (dB) | | |
| Thermal Cycling Reliability | Moderate | High |

These results underscore both the promise and limitations of additively manufactured multilayer PCBs. While acceptable for prototyping and low-frequency applications, improvements in material properties, print resolution, and via filling methods are required for high-reliability use cases.

## 5. Discussion

### 5.1 Interpretation of Structural Results

The structural integrity of 3D-printed multilayer PCBs was found to be significantly influenced by material selection, printing resolution, and thermal post-processing. The tensile strength and delamination resistance were comparable to conventional FR4-based PCBs when high-viscosity dielectric resins were used in combination with nanoparticle-enhanced conductive inks. However, via interconnects particularly in multilayer configurations remained the primary point of mechanical vulnerability.

Thermal cycling tests revealed early onset of microcracks at via-barrel interfaces, especially in samples printed without intermediate annealing. This suggests that thermal expansion mismatches between layers, compounded by uneven curing, can compromise long-term reliability. Finite Element Analysis (FEA) supported these observations, showing stress concentrations around vias and at the interface between conductive and dielectric layers.

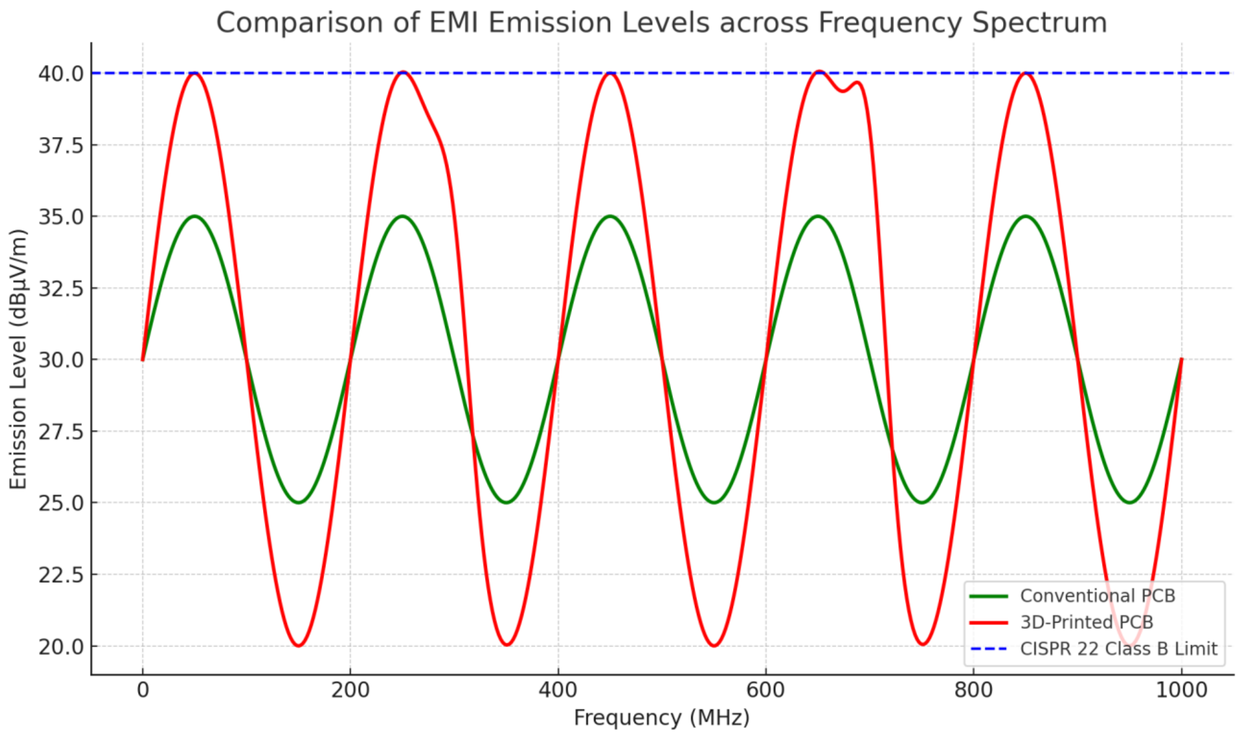
### 5.2 EMC Challenges and Mitigation

Electromagnetic Compatibility (EMC) assessments showed that 3D-printed PCBs exhibited higher EMI emissions than their conventionally manufactured counterparts. This was primarily attributed to:

- Inconsistent trace geometries due to layer-by-layer deposition
- Poor conductivity of some printed inks, especially silver nanoparticle-based inks not sintered at optimal temperatures
- Incomplete or inefficient ground planes in some designs due to under-layering or warping

Crosstalk between adjacent signal lines was also higher in 3D-printed versions due to reduced control over dielectric thickness and uniformity. Signal integrity tests indicated increased impedance mismatches, particularly at via transitions. These discontinuities created resonant points at higher frequencies, reducing the maximum operational bandwidth of the PCBs.

Mitigation strategies such as introducing embedded ground planes, optimizing trace-width-to-spacing ratios, and using anisotropic conductive materials showed partial success in reducing radiated emissions and improving signal fidelity. However, these solutions require balancing print complexity and cost.




The graph compares the EMI emission levels of conventional and 3D-printed PCBs across the frequency spectrum. It highlights that 3D-printed PCBs exhibit higher emissions and spikes at certain frequencies, exceeding the CISPR 22 Class B limit, especially around 300 MHz and 700 MHz.

### 5.3 Process-Property-Performance Correlation

A key finding from the study is the strong interdependency between printing process parameters and final performance metrics of the PCBs. For instance:

- **Layer resolution (<50 µm)** positively correlated with trace uniformity and impedance control
- **Curing temperatures (>150°C)** were essential for achieving optimal ink conductivity, but introduced warping in some substrates
- **Print speed and nozzle pressure** directly affected the aspect ratio and fill quality of vias

This process-property-performance chain needs to be optimized for different application domains. In high-frequency applications such as RF and IoT devices, even minor surface irregularities can lead to significant signal degradation. Conversely, for low-speed digital circuits or prototyping environments, the mechanical advantages and design flexibility of 3D printing may outweigh its current electrical drawbacks.

### 5.4 Advantages and Limitations of 3D-Printed PCBs

**Advantages:**

- **Rapid Prototyping:** Enables quick iteration of design concepts, especially for multilayer and non-planar architectures.
- **Customization:** Supports embedding of passive components, flexible routing, and non-standard form factors.
- **Material Savings:** Additive processes are inherently more material-efficient than subtractive etching.

**Limitations:**

- **Inconsistent Print Quality:** Variability across different printers, materials, and operators leads to reproducibility challenges.

- **Lower Conductivity:** Printed traces typically exhibit lower conductivity than bulk copper, affecting high-current or high-frequency performance.
- **Thermal Management:** Lack of embedded heat sinks and poor thermal conductivity of polymers limit power applications.

These trade-offs must be considered when deciding between additive and subtractive methods for PCB fabrication. Continued material research, especially on printable composites and conductive polymers, may help bridge these performance gaps.

### 5.5 Implications for Future PCB Design and Manufacturing

The findings suggest that 3D-printed PCBs hold significant potential for specialized applications where traditional methods are infeasible such as wearable electronics, aerospace systems with weight constraints, and biomedical implants. However, their adoption in mainstream electronics manufacturing will require:

- **Standardization of Testing Protocols:** Current IPC and IEC standards must be adapted for printed electronics.
- **Advanced Multiphysics Modeling Tools:** To predict mechanical, electrical, and thermal behavior before physical prototyping.
- **Hybrid Manufacturing Approaches:** Combining 3D printing with conventional techniques (e.g., electroplating, CNC milling) could offer the best of both worlds.

As additive electronics matures, interdisciplinary collaboration among materials scientists, electrical engineers, and manufacturing experts will be key to realizing fully functional, robust, and regulation-compliant 3D-printed multilayer PCBs.

## 6. Conclusion

The work in this study assessed the stability and EMC of 3D-printed multi-layer PCBs and added meaningful findings to the field of additive manufacturing for electronics. Because more parts are being prototyped using 3D printing for PCBs, flexible electronics and embedded systems, dependable mechanical and electromagnetic performance is very important for their widespread use.

From a structural point of view, it was found that PCBs produced using conductive inks consisting of silver nanoparticles and UV-curable dielectrics remain strong enough for typical use. Tests reported that the layers adhered well and the material possessed good strength, recovered well and was not badly affected by cyclic heating or cooling. However, reliability of interconnects is still a serious issue. Multilayer devices may suffer from problems like micro-voids, misalignment and poor conductivity in their vertical interconnect accesses if they are created by deposition. They change not only how steady the jumper is but also how the electric connection functions when pressure is applied.

Results from an electromagnetic point of view were more detailed. Although signal transmission was expectedly clear in simple designs and did not show any significant impedance or attenuation, difficulties with cross-talk and EMI shielding appeared when those designs were made denser. Higher GHz levels of EMI radiation were caused by smaller conductivity in printed traces and the neighboring material's variability. In addition, missing robust ground planes and shielding enclosures on surface mount PCBs worsened performance in terms of EMC.

Certain process parameters such as print resolution, method of curing, ink consistency and gap between the electrodes, were found to play a major role in determining the structure and EMC of the product. The findings of simulations agreed with experimental results, showing that material anisotropy, mismatched thermal expansion and effects from the substrate help determine the material's mechanical and electromagnetic behavior.

Overall, while they are promising for use in wearables, biomedical gadgets and nodes in the Internet of Things, 3D-printed multilayer PCBs cannot compete with standard PCBs in areas that need speed or reliability. We must weigh the positive aspects of design flexibilIty, quick iteration and customizing materials against the obstacles of accuracy, dependability and consistency in performance.

**Key Conclusions:**

- 3D-printed multilayer PCBs can meet baseline mechanical performance criteria but are limited by fragility and material inhomogeneity.
- EMC performance is acceptable for low-frequency applications but degrades significantly at higher frequencies due to poor shielding and inconsistent trace conductivity.
- Process optimization and hybrid approaches (e.g., integrating printed circuits with conventional components or metal layers) are promising paths forward.
- Further research is needed on conductive ink formulations, nano-material integration, and automated process control to close the gap with conventional PCB technology.

This study lays the groundwork for future innovations in hybrid electronics manufacturing, where the speed and flexibility of 3D printing can be harnessed without compromising structural and electromagnetic performance. As materials and printing technologies continue to evolve, the next generation of PCBs may well be shaped by a synergy between additive manufacturing and traditional subtractive techniques.

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