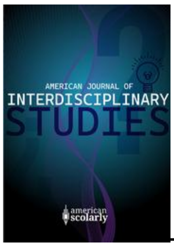

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MULTI-MATERIAL ADDITIVE MANUFACTURING FOR INTEGRATED ELECTROMECHANICAL SYSTEMS

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Abstract
Multi-material additive manufacturing (MMAM) has emerged as a disruptive technological advancement that redefines the fabrication of integrated electromechanical systems by enabling the co-deposition of dissimilar materials—such as conductors, insulators, structural polymers, and elastomers—within a single, layer-by-layer printing process. Unlike conventional manufacturing techniques that require multiple fabrication and assembly stages to integrate mechanical and electrical components, MMAM allows for the simultaneous realization of structural integrity and functional performance in compact, lightweight, and geometrically complex devices. The objective of this study is to conduct a comprehensive meta-analysis of empirical research on MMAM, systematically evaluating its capabilities, performance metrics, and application outcomes across domains such as aerospace, biomedical engineering, soft robotics, and consumer electronics. Following PRISMA guidelines, a total of 122 peer-reviewed studies published between 2010 and 2023 were selected from major academic databases. Data were extracted on material types, fabrication methods, interface strategies, application domains, and quantitative performance outcomes related to mechanical strength, conductivity, interfacial adhesion, and system-level reliability. Effect sizes were computed using a random-effects model, and heterogeneity and publication bias were statistically assessed. The meta-analysis revealed substantial improvements in tensile and shear strength, often ranging between 15% and 35%, when using reinforced or hybrid MMAM techniques compared to monomaterial counterparts. Interface stability was enhanced through the use of micro-patterned geometries, graded material transitions, and in-situ curing strategies, which significantly reduced delamination and warping. Application-specific findings showed that MMAM enabled the fabrication of prosthetics with embedded EMG sensors, soft robotic actuators with integrated strain gauges, and structural aerospace components with in-built diagnostic sensors—all within single uninterrupted manufacturing cycles. Furthermore, lifecycle analysis confirmed higher fatigue resistance, sensor stability, and environmental resilience across embedded systems, supporting MMAM's viability for deployment in demanding operational environments. The results conclusively position MMAM as a scalable and multifunctional fabrication platform capable of producing integrated electromechanical systems with enhanced performance, reduced complexity, and unprecedented design freedom. This study provides critical insights into MMAM's current state-of-the-art and its broad potential to transform both industrial manufacturing and functional prototyping in high-performance sectors.

Keywords
Multi-Material Additive Manufacturing, Integrated Electromechanical Systems, Functional Materials, 3D Printing, Embedded Electronics

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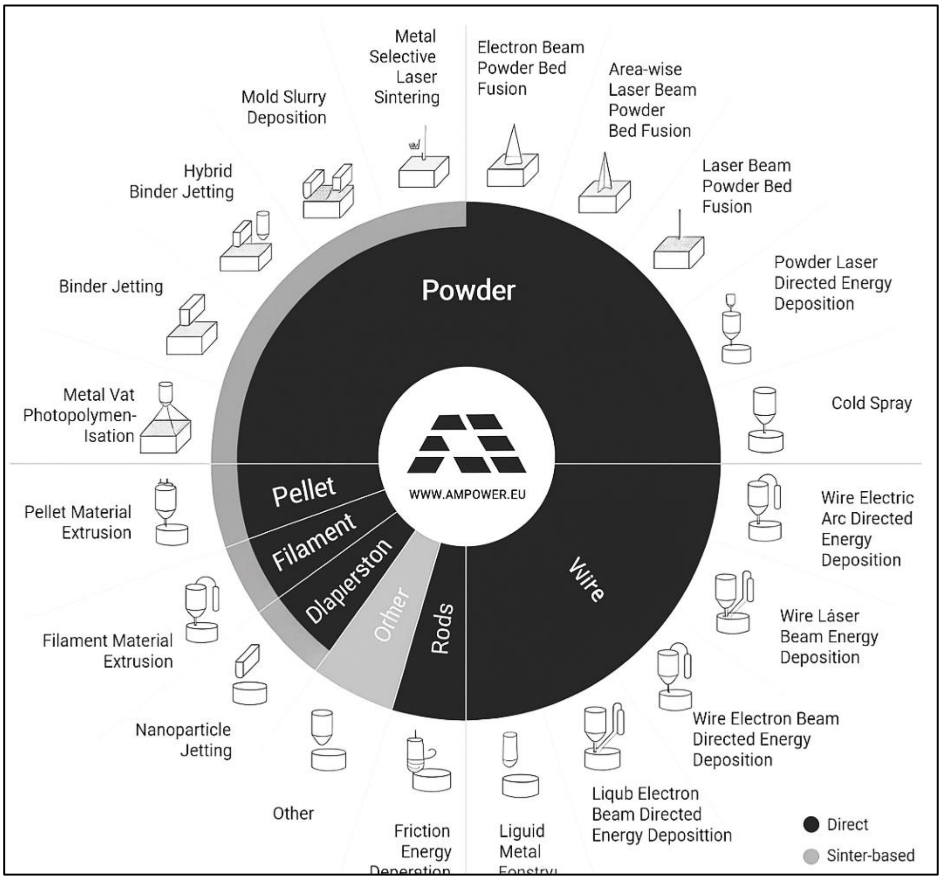
INTRODUCTION

Additive manufacturing (AM), commonly referred to as 3D printing, is a layer-by-layer fabrication process where digital designs are translated into physical objects through material deposition. The process contrasts traditional subtractive manufacturing by enabling the construction of geometrically complex structures with minimal material waste (Tiismus et al., 2021). Among the numerous evolutions of AM, multi-material additive manufacturing (MMAM) refers to the integration of two or more dissimilar materials—such as polymers, metals, ceramics, and conductive inks—within a single print job to create components with diverse functionalities (Lu et al., 2018). This capability is particularly essential in fabricating electromechanical systems, where electrical and mechanical functions must coexist within tightly coupled architectures. MMAM serves as a critical tool in creating integrated devices where embedded sensors, circuits, or actuators are inseparable from the mechanical frame (Dzogbewu et al., 2021). As the boundaries between functional and structural elements blur, MMAM becomes essential in areas such as biomedical prosthetics, autonomous robotics, aerospace, and wearable electronics.

Figure 1: Metal Additive Manufacturing Process Classification



The international relevance of MMAM is underscored by its alignment with the goals of Industry 4.0, where intelligent manufacturing processes are driven by data integration, automation, and advanced material use. The European Union's Horizon 2020 program and the United States' National Additive Manufacturing Innovation Institute (NAMII) have placed significant emphasis on developing multi-material capabilities for advanced manufacturing (Koopmann et al., 2019). The ability to combine conductive paths with insulating frameworks or soft materials with rigid supports enables the seamless development of electromechanical devices without the need for extensive post-processing or assembly (Lakhdar et al., 2021). In countries like Germany, Japan, and the United States, MMAM is regarded as a strategic technology for national competitiveness in high-value manufacturing sectors. The applications of MMAM extend to mission-critical industries, such as

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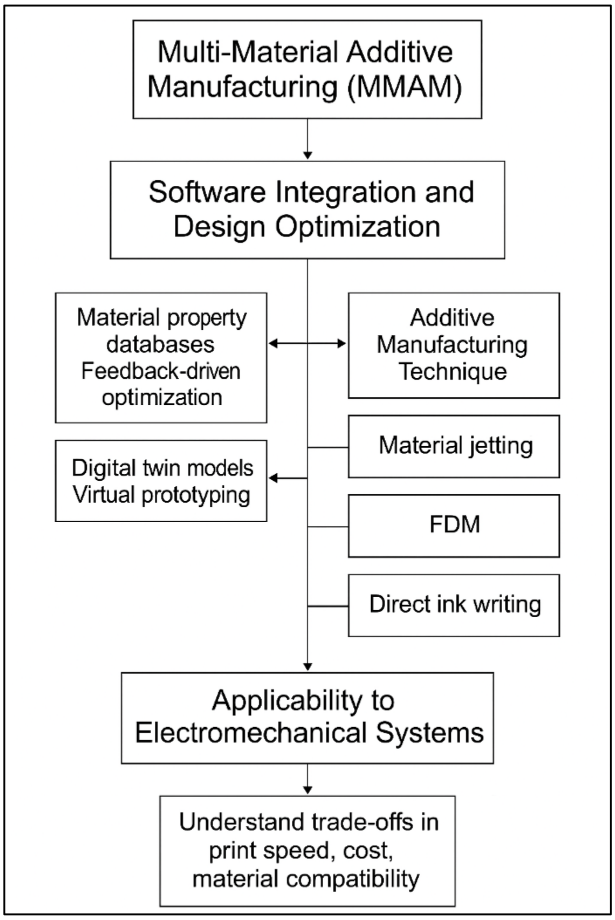
aerospace where weight reduction and functionality integration are vital, and in personalized medicine where biocompatible multi-material scaffolds are needed for patient-specific implants (Zadpoor & Malda, 2016). At the core of MMAM lies material compatibility and process integration, which are central challenges to building robust electromechanical systems. Traditional single-material AM processes often fall short when tasked with fabricating objects that demand both electrical conductivity and mechanical strength. MMAM bridges this gap by allowing for simultaneous or sequential deposition of diverse material classes using technologies such as inkjet printing, fused deposition modeling (FDM), and direct ink writing (DIW). For example, researchers have integrated conductive silver nanoparticle inks and structural thermoplastics within one build process to create embedded circuitry within flexible substrates (Zocca et al., 2015). Similarly, printed strain sensors using conductive elastomers alongside rigid casings exemplify how MMAM enables mechanical-electrical integration without compromising design fidelity. These advances facilitate the design of systems with embedded functionalities, such as antennas, power delivery units, or capacitive touch interfaces. However, ensuring adhesion between dissimilar materials and maintaining thermal and mechanical stability during the build process remain key research challenges (Hensleigh et al., 2018).

Another critical area of development in MMAM is software integration and design optimization. Unlike traditional CAD environments that assume homogeneous materials, MMAM design tools must accommodate spatially variant material properties and co-design of function and form (Zhang et al., 2021). Finite element modeling (FEM) and topology optimization algorithms have been increasingly utilized to simulate stress distribution, electrical conductivity, and thermal expansion in multi-material constructs before fabrication (Kang et al., 2021). This integrated design-simulation-manufacture pipeline is essential for devices like stretchable electronics or piezoelectric actuators where mechanical deformation directly influences electrical performance (Tiismus et al., 2021). Moreover, material property databases and feedback-driven optimization approaches have emerged to streamline the design process in MMAM environments. As a result, digital twin models and virtual prototyping are playing a larger role in MMAM system design, offering designers predictive insights into device behavior under real-world conditions. The choice of additive manufacturing technique in MMAM directly influences the resolution, interfacial strength, and functional yield of electromechanical systems. Material jetting, for example, is well-suited for fine-feature conductive inks but may suffer from limited structural robustness (Lu et al., 2018).

Figure 2: Software Integration and Process Optimization Pipeline



FDM, while versatile for polymers, poses challenges when integrating metals or ceramics due to high temperature gradients (Dzogbewu et al., 2021). Direct ink writing has emerged as a promising hybrid solution, offering precise material placement with the ability to extrude pastes or gels embedded with functional nanoparticles (Zadpoor & Malda, 2016). Each of these techniques offers trade-offs in print speed, cost, and material compatibility. Researchers have also experimented with hybrid setups that combine multiple print heads or energy sources—such as laser sintering combined with polymer extrusion—to enhance multi-material integration. Understanding these trade-offs is critical for fabricating electromechanical components such as printed sensors, embedded coils, or micromechanical switches (Zocca et al., 2015).

Material selection is pivotal to MMAM's success, especially when fabricating electromechanical devices where conductivity, elasticity, thermal resilience, and mechanical strength must be balanced. Conductive inks based on silver, copper, or carbon nanotubes are widely employed for electrical pathways, while structural supports often utilize thermoplastics like PLA, ABS, or polycarbonate (Hensleigh et al., 2018). Elastomers such as PDMS are favored for soft robotics applications, while piezoelectric and magnetostrictive materials are increasingly explored for actuation and sensing functions. The interplay between these materials influences not only functional outcomes but also printability and interlayer bonding quality (Zhang et al., 2021). Researchers have noted that tuning viscosity, curing temperature, and surface energy parameters significantly improves compatibility across dissimilar interfaces (Goh et al., 2021). Moreover, functional grading—where material properties transition gradually across a part—has become an effective strategy for minimizing delamination and improving device longevity. The applicability of MMAM in electromechanical systems is evidenced by a growing body of case studies across high-impact sectors. In biomedical engineering, multi-material 3D printing has enabled the creation of prosthetic limbs with embedded myoelectric sensors that adapt to user inputs. Aerospace engineers have utilized MMAM to fabricate lightweight structural brackets with embedded sensors for real-time stress monitoring. In consumer electronics, printed antennas and capacitive sensors have been integrated directly into device housings, reducing part counts and improving design compactness (Wei et al., 2018). Robotics applications, too, have seen the integration of soft joints, flexible circuitry, and embedded feedback sensors using MMAM, thereby enabling compliant motion and real-time control. These examples underscore the versatility of MMAM in enabling compact, multifunctional systems tailored to specific operational demands and user environments. Lastly, quality assurance, reliability, and scalability are pressing issues in MMAM that directly influence its adoption for integrated electromechanical systems. Conventional non-destructive evaluation (NDE) methods are often inadequate for inspecting multi-material prints due to material heterogeneity and complex internal geometries. Researchers have developed in-situ monitoring techniques, such as optical coherence tomography, acoustic sensors, and electrical resistance measurement, to track print integrity during fabrication. Statistical process control methods and machine learning models are also being employed to detect anomalies and predict part failures before they propagate (Khoo et al., 2015). Furthermore, lifecycle analysis and performance benchmarking are being used to compare MMAM-fabricated electromechanical systems with their conventionally manufactured counterparts in terms of durability, environmental impact, and cost. These dimensions underscore the growing maturity of MMAM as a viable platform for integrated systems engineering.

The primary objective of this research is to systematically explore and evaluate the current advancements, fabrication techniques, material compatibility challenges, and real-world applications of multi-material additive manufacturing (MMAM) for integrated electromechanical systems. Specifically, this study aims to examine how MMAM technologies enable the concurrent integration of structural, conductive, and functional materials within a single manufacturing process to support the development of embedded electromechanical devices. This includes analyzing additive methods such as inkjet printing, fused deposition modeling (FDM), and direct ink writing (DIW) in the context of multi-material co-deposition. By focusing on fabrication strategies, this research intends to identify the conditions under which dissimilar materials—including polymers, metals, ceramics, elastomers, and nanomaterials—can be effectively combined to produce cohesive, high-performance systems with both electrical and mechanical functionalities. The study further seeks to identify design methodologies, simulation tools, and material processing frameworks that facilitate the co-design of structural and functional components. Moreover, this research investigates the applicability of MMAM across key industrial sectors such as biomedical engineering, aerospace, robotics, and consumer electronics, with particular attention to use cases that demand lightweight construction, functional miniaturization, and real-time responsiveness. Through this objective, the study will contribute to a better understanding of the material-process-performance relationship in MMAM systems and assess the extent to which MMAM can replace or enhance traditional manufacturing methods for electromechanical integration. Furthermore, the study aims to document in-situ monitoring techniques, interfacial quality assurance strategies, and post-processing considerations required for producing reliable multi-material parts. Ultimately, the objective is to synthesize empirical findings and engineering practices that inform the scalable, cost-effective, and robust implementation of MMAM in the design and production of next-generation integrated electromechanical systems.

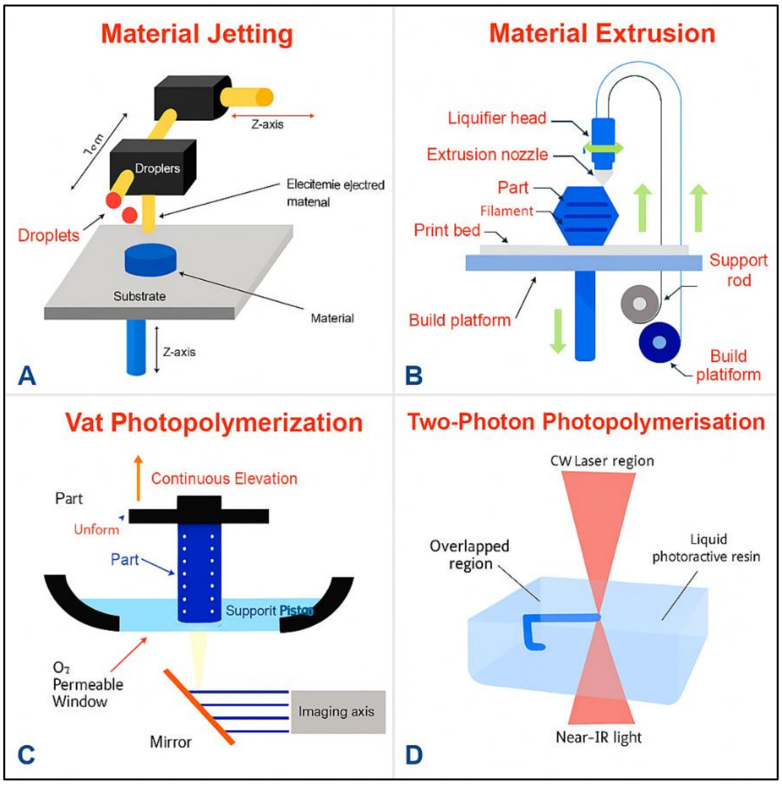
LITERATURE REVIEW

The advancement of additive manufacturing has ushered in a paradigm shift in how complex electromechanical systems are designed and produced. Among the various developments, multi-material additive manufacturing (MMAM) has emerged as a pivotal innovation, allowing the simultaneous or sequential deposition of heterogeneous materials within a unified fabrication environment. This capability has profound implications for the creation of devices that combine mechanical, electrical, thermal, and sometimes biological functions in a single structure. The body of scholarly work on MMAM spans disciplines including materials science, mechanical engineering, electrical engineering, and industrial design, reflecting its multidisciplinary nature. The literature reveals diverse approaches to addressing material compatibility, structural integrity, interfacial adhesion, process control, and functional performance. Moreover, the development of new printing techniques, compatible materials, and design methodologies has significantly broadened the application domains of MMAM—from aerospace systems and soft robotics to biomedical devices and consumer electronics. This literature review provides a structured synthesis of existing academic and technical research on MMAM as applied to integrated electromechanical systems. It begins by examining the foundational printing techniques and their suitability for multi-material fabrication. The review then explores the properties and roles of functional and structural materials, emphasizing how material selection impacts printability, electrical conductivity, and mechanical performance. Next, it investigates the challenges in multi-material integration, including interfacial bonding, thermal mismatch, and material degradation. The discussion is extended to include software-enabled design strategies, simulation techniques, and computational modeling required for MMAM implementation. Finally, the literature review identifies key industrial applications and summarizes emerging quality control methods and reliability assessments that ensure the long-term viability of printed electromechanical devices.

Additive Manufacturing

Additive manufacturing (AM), often referred to as 3D printing, has undergone significant technological and conceptual transformations since its inception in the 1980s. Initially designed for rapid prototyping, AM has evolved into a full-fledged production methodology capable of fabricating end-use parts across various industries. Early technologies such as stereolithography (SLA) and selective laser sintering (SLS) laid the groundwork for high-resolution, layer-wise fabrication, offering design freedom that traditional subtractive manufacturing could not match (Hu et al., 2020). The expansion of AM into multiple domains was facilitated by the emergence of diverse printing methods, including fused deposition modeling (FDM), digital light processing (DLP), and direct energy deposition (DED), each suited for specific material classes and resolution requirements (Arif et al., 2022). As AM matured, researchers began to exploit its ability to fabricate geometrically complex structures with internal voids, lattice architectures, and conformal surfaces, particularly in the biomedical and aerospace sectors. The advantages of AM extend beyond geometry; material efficiency, reduced lead time, and the ability to localize production have driven its adoption in industrial workflows (Lu et al., 2018). However, technical limitations persist. Challenges such as surface roughness, anisotropic mechanical properties, and limited material selection continue to restrict broader implementation in high-precision applications . The rise of metal-based AM processes like powder bed fusion (PBF) and binder jetting further expanded AM's role in manufacturing functional components, particularly in energy, defense, and automotive sectors. Collectively, the literature demonstrates that the foundation of additive manufacturing provides a versatile platform that is being further extended by the integration of multi-material capabilities.

Figure 3: Schematic Overview of Four Distinct Additive Manufacturing Techniques with Enhanced Annotations



The versatility of additive manufacturing is inherently tied to the range of materials it can process. Traditional AM systems are predominantly optimized for single-material deposition, often favoring thermoplastics like acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polycarbonate for FDM processes, while metals such as titanium alloys, stainless steels, and aluminum are widely employed in SLS and direct metal laser sintering (DMLS) (Dzogbewu et al., 2021). Despite these advances, the monomaterial constraint in conventional AM presents limitations in developing multifunctional or integrated systems. For example, printing conductive circuits alongside structural frames in a single build remains infeasible in many standard systems due to differences in melting point, viscosity, and processing conditions (Koopmann et al., 2019). Moreover, polymer-based AM processes often yield parts with poor thermal stability and reduced mechanical strength compared to their injection-molded counterparts. Studies have also highlighted that the mechanical anisotropy in printed parts, caused by layer-wise bonding, can result in unpredictable performance under load. In metal-based AM, residual stress due to thermal gradients during layer fusion remains a significant barrier to structural integrity. The introduction of composite filaments and reinforced polymers has improved specific mechanical properties, yet the multifunctional potential of AM remains largely unrealized without the integration of multiple materials possessing distinct electrical, thermal, and mechanical characteristics. Researchers have begun exploring the co-extrusion of dissimilar materials, but issues of interfacial bonding and real-time process control remain unresolved (Koopmann et al., 2019). Hence, the literature underscores that while AM offers design flexibility, its true potential is curtailed by inherent material limitations in traditional single-feed systems.

Multi-material additive manufacturing (MMAM) emerges as a response to the limitations of monomaterial AM systems, enabling the co-fabrication of components with distinct functional and structural properties. MMAM involves the simultaneous or sequential deposition of multiple materials, allowing for the integration of conductive, dielectric, and mechanical elements in a single fabrication cycle. This innovation is particularly valuable in developing integrated electromechanical systems such as embedded sensors, wearable electronics, and soft robotic actuators (Bandyopadhyay & Heer, 2018). Inkjet printing, direct ink writing (DIW), and hybrid FDM systems are frequently used MMAM techniques, each offering unique benefits depending on the

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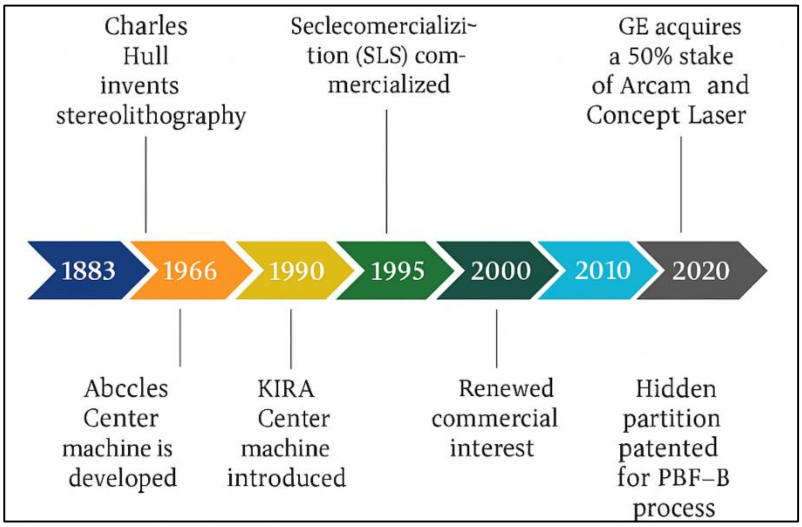
material class and resolution required (Eckel et al., 2016). For instance, DIW has been employed to fabricate stretchable electronics by extruding conductive pastes alongside elastomeric substrates (Simpson et al., 2020). Similarly, inkjet systems allow selective deposition of nanoparticle-based conductive inks onto thermoplastic surfaces, forming embedded circuits (Tan et al., 2021). Nevertheless, MMAM systems face significant technical challenges, particularly in achieving strong interfacial adhesion between dissimilar materials and maintaining print fidelity at material junctions (Falck et al., 2018). Thermal and chemical incompatibilities may lead to delamination, warping, or inconsistent conductivity across printed paths. Researchers have proposed using functional grading and surface modification to enhance interlayer bonding, which has shown promising results in enhancing mechanical and electrical performance. Software tools enabling voxel-based design and real-time print control have further improved precision in MMAM (Bandyopadhyay et al., 2022).

Additive Manufacturing and MMAM Evolution

Additive manufacturing (AM), since its earliest conceptualization, has offered a novel paradigm in product development, shifting from traditional subtractive and formative methods to a digitally driven, layer-by-layer material deposition process. The pioneering work of Charles Hull in stereolithography (SLA) during the 1980s marked the commercial birth of 3D printing (Brancewicz-Steinmetz & Sawicki, 2022), which was quickly followed by other core technologies such as selective laser sintering (SLS) and fused deposition modeling (FDM) (Pragana et al., 2020). Initially envisioned as a tool for rapid prototyping, AM soon demonstrated capability in fabricating complex geometries and customized parts with minimal material waste. The global industrial sectors, especially aerospace and biomedical, began to adopt AM due to its potential to produce lightweight structures, patient-specific implants, and design freedom (Hofmann et al., 2014). The transition from prototyping to direct manufacturing was accelerated by enhancements in material availability, print resolution, and process repeatability. However, initial AM systems were largely constrained to single-material printing, resulting in limited functionality within fabricated components. The anisotropic mechanical properties and surface finish issues of early AM parts also restricted their adoption in critical applications (Binder et al., 2019). As the technology matured, attention shifted toward expanding the range of processable materials and integrating functional properties, thus paving the way for multi-material additive manufacturing (MMAM) systems. The literature thus positions the evolution of AM as foundational, where the need for multifunctional, integrated systems catalyzed a shift from geometric to functional complexity.

Figure 4: Condensed Timeline of Key Milestones in Additive Manufacturing Development



The limitations of monomaterial AM systems, especially their inability to integrate diverse functionalities within a single structure, prompted the emergence of multi-material additive

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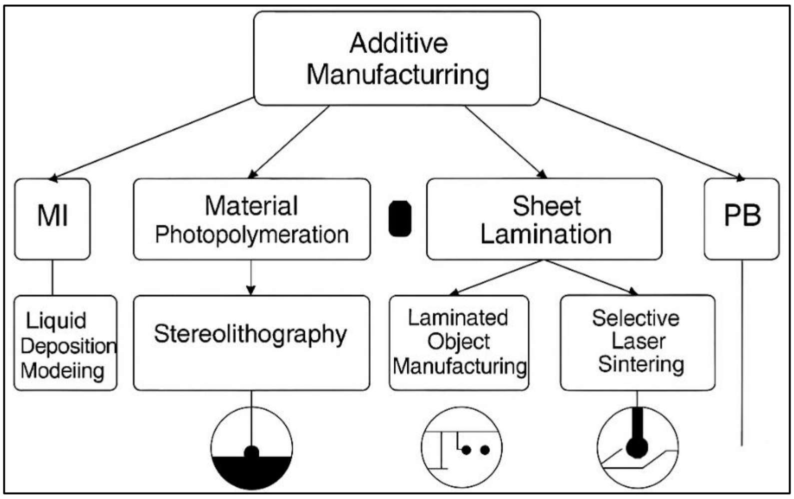
manufacturing (MMAM). MMAM is characterized by its ability to deposit two or more dissimilar materials—typically a combination of structural, conductive, and responsive materials—within a single print cycle, enabling the creation of fully integrated electromechanical systems (Perez & Williams, 2014). This shift significantly broadened the scope of 3D printing from mere geometric design to the co-fabrication of structures with embedded sensors, circuits, and actuators (Pragana et al., 2020)Technologies such as inkjet-based printing, direct ink writing (DIW), and multi-head fused filament fabrication (FFF) have been central to MMAM's advancement, each offering unique advantages in material placement, resolution, and process control ((Li et al., 2019). For instance, DIW has been utilized to print conductive carbon- and silver-based inks alongside elastomeric substrates to fabricate soft sensors and stretchable electronics (Tiismus et al., 2021). However, MMAM evolution has not been without challenges. Achieving reliable interfacial adhesion, thermal compatibility, and dimensional precision between materials with differing mechanical and chemical properties remains a critical barrier. Researchers have explored methods such as surface energy modification, functional gradient transitions, and co-curing strategies to mitigate these issues. Recent developments also focus on hybrid systems that combine photopolymerization, sintering, and extrusion to improve integration flexibility and application range.

Classification of Multi-Material Printing Techniques

Inkjet-based and material jetting technologies represent foundational techniques in multi-material additive manufacturing (MMAM), particularly for applications requiring high precision in the deposition of functional inks. Inkjet printing enables selective deposition of low-viscosity materials—commonly nanoparticle-based conductive inks—on a substrate, which can be sequentially cured using ultraviolet or thermal energy sources (MacDonald et al., 2014). This technique allows for spatially controlled deposition of conductive, dielectric, and even biological materials, making it suitable for printed electronics, biosensors, and lab-on-a-chip systems (Espalin et al., 2014). Material jetting systems, such as PolyJet and MultiJet, extend this capability by allowing simultaneous jetting of photopolymer resins with varied mechanical properties, enabling the creation of parts with graded stiffness, transparency, or elasticity (Yuk et al., 2020). These technologies have been applied in fabricating tactile sensors, microfluidic channels, and even artificial skin by co-printing soft and rigid polymers in alternating patterns (Martin et al., 2017). One limitation, however, is their restricted material palette; only inks with a narrow viscosity and particle size range can be effectively ejected (Goh et al., 2021). Moreover, interlayer adhesion and resolution are sensitive to surface energy mismatch and thermal expansion between materials (Wei et al., 2018). Researchers have employed surface pre-treatment, plasma activation, and in-situ curing techniques to overcome adhesion limitations (Khoo et al., 2015). Inkjet systems are also often integrated with automated alignment tools for high-resolution multi-pass printing of multilayered circuits or embedded sensors (Arif et al., 2022). The literature collectively indicates that inkjet-based MMAM offers superior resolution and functional versatility, albeit with trade-offs in mechanical strength and material diversity.

Fused deposition modeling (FDM) is among the most widely adopted additive manufacturing techniques and has been extended into multi-material applications through the use of multi-nozzle or multi-filament systems. In its conventional form, FDM involves extruding thermoplastic filaments through a heated nozzle, layer by layer, to form a three-dimensional object (Khalid, Arif, Noroozi, et al., 2022). In MMAM, multiple extruders enable the simultaneous or sequential deposition of different thermoplastics, conductive filaments, or composite materials, allowing the fabrication of components that combine structural integrity with electrical functionality (Espalin et al., 2014). One notable advantage of multi-nozzle FDM is its compatibility with a broad range of commercially available filaments, such as PLA, ABS, TPU, and conductive carbon-black-infused polymers. Applications include printed circuit boards, conformal antennas, and embedded sensor housings. However, nozzle switching and thermal lag present challenges in print continuity and material purity, often leading to cross-contamination or delayed transitions between material phases (Ge et al., 2014). Moreover, interfacial bonding between dissimilar materials remains a concern, especially when combining flexible and rigid polymers or integrating conductive and insulating layers. Solutions proposed in the literature include dual-head temperature control, print path optimization, and the use of bonding layers or adhesives (Christ et al., 2018). Hybrid FDM systems incorporating print-bed heating, automated calibration, and real-time sensing have improved interlayer alignment and part quality (Shim et al., 2012). Thus, multi-nozzle FDM emerges as a cost-effective, accessible, and scalable method for producing functionally integrated parts, especially when combined with optimized thermal and mechanical processing conditions.

Figure 5: Simplified Classification of Additive Manufacturing Processes

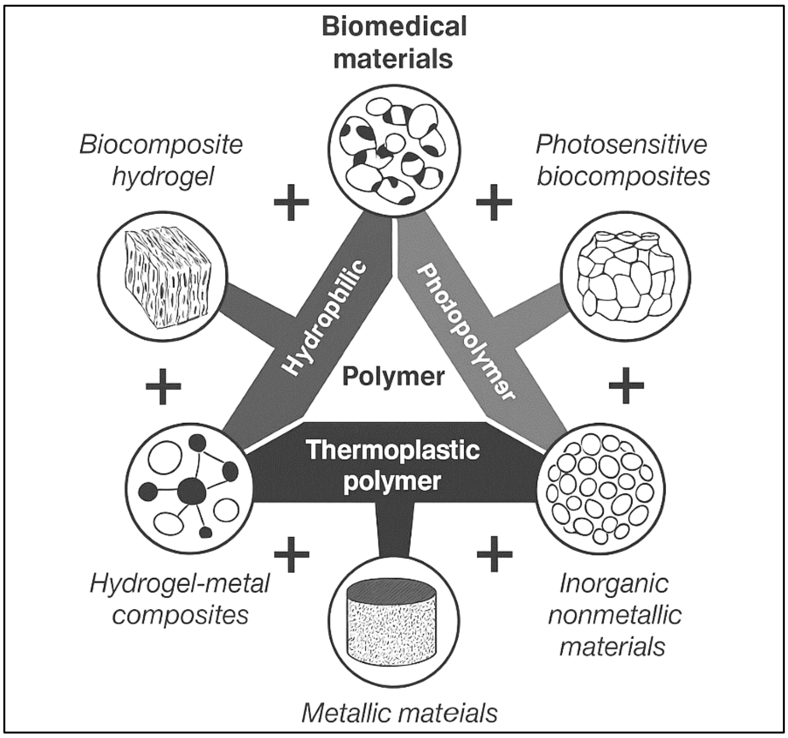


Direct ink writing (DIW) and other extrusion-based printing methods have proven exceptionally versatile in MMAM due to their ability to process a wide variety of materials with diverse rheological properties. DIW operates by extruding pastes, gels, or viscoelastic inks through fine nozzles under controlled pressure, allowing the co-printing of structural materials, conductive inks, and functional nanocomposites within a single build (Lu et al., 2018). Unlike FDM, which is limited to thermoplastic filaments, DIW accommodates materials ranging from silicone elastomers to silver nanoparticle inks and carbon nanotube suspensions (Mostafaei et al., 2021). This technique has been successfully used to create stretchable electronics, hybrid sensors, and battery components with embedded electrodes (Khalid, Arif, & Ahmed, 2022). DIW's ability to print on curved and flexible substrates further enhances its utility in soft robotics and biomedical applications (Arif et al., 2022). However, extrusion-based MMAM systems often suffer from lower resolution compared to inkjet or laser-based techniques, and controlling intermaterial diffusion and print path overlap is a persistent challenge (Khoo et al., 2015). Print fidelity is heavily influenced by ink viscosity, shear thinning behavior, and nozzle-substrate distance (Wei et al., 2018). Researchers have addressed these challenges by formulating shear-thinning inks with programmable rheological profiles and by incorporating in-situ curing mechanisms (Kuang et al., 2018). DIW setups have also been integrated with robotic arms and machine vision systems to enable multi-axis, freeform, and conformal printing (Martin et al., 2017).

Functional Materials for MMAM Applications

Conductive materials form the backbone of MMAM applications aimed at integrating electronic functions such as signal transmission, sensing, and power distribution. Among these, silver-based inks are the most widely researched due to their superior electrical conductivity, printability, and relatively low sintering temperatures (Bodkhe & Ermanni, 2019). These nanoparticle inks are particularly well-suited for inkjet and direct ink writing (DIW) techniques, allowing the creation of fine conductive traces on both rigid and flexible substrates. However, the high cost and oxidation susceptibility of silver have motivated the exploration of copper-based alternatives, which offer comparable conductivity at a lower price point. The major challenge with copper inks lies in their tendency to oxidize rapidly, which degrades performance unless processed in inert atmospheres or with protective coatings. In parallel, carbon-based inks—comprising carbon nanotubes, graphene, and graphite composites—have gained prominence for their flexibility, low toxicity, and chemical stability. These materials are especially relevant in flexible electronics, printed sensors, and stretchable interconnects, where their moderate conductivity is offset by high mechanical compliance (Savitha et al., 2015). Moreover, composite inks that combine metallic nanoparticles with carbon matrices have been developed to balance conductivity and flexibility in wearable devices. Researchers have also explored rheological modifications and surfactant additives to enhance the printability and dispersion quality of conductive inks in MMAM platforms (Xia et al., 2019). These studies indicate that the choice of conductive material must align with application-specific requirements such as current density, flexibility, and environmental stability, which directly influence MMAM process selection and final device performance.

Figure 6: Polymer Combinations and Composite Material Classes in Multi-Material Additive Manufacturing



Piezoelectric and magnetostrictive materials serve as critical functional components in MMAM when actuation, energy harvesting, or sensing capabilities are required. Piezoelectric materials, which generate electric charge in response to mechanical stress, have been widely adopted in printed sensors, haptic devices, and microactuators (Derby, 2010). Lead zirconate titanate (PZT), one of the most studied piezoelectric ceramics, has been incorporated into printable ink formulations to fabricate flexible pressure sensors and energy harvesters via direct ink writing and aerosol jet printing (Campoli et al., 2013). Although PZT provides excellent piezoelectric properties, its brittleness and toxicity due to lead content have spurred the development of lead-free alternatives such as barium titanate ($BaTiO_3$) and potassium sodium niobate (KNN) (Xia et al., 2019). These materials, when integrated with polymer matrices like PVDF (polyvinylidene fluoride), offer printable composites with both flexibility and functionality. On the other hand, magnetostrictive materials—those that deform under magnetic fields—enable MMAM applications in wireless actuators, vibration sensors, and magnetically controlled systems. Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_2$) and Galfenol (FeGa alloys) are among the most prominent magnetostrictive materials used in 3D printing, often in filament or slurry form. These materials pose processing challenges due to their thermal sensitivity and need for precise magnetic alignment during deposition (Wang et al., 2021). To mitigate these issues, studies have explored hybrid printing strategies that integrate magnetic field-assisted alignment with DIW or multi-axis extrusion. Both piezoelectric and magnetostrictive materials are instrumental in advancing the

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functionality of MMAM-fabricated devices, particularly in sectors requiring dynamic responsiveness, embedded feedback, and smart material behavior.

Materials in Electromechanical Systems

Thermoplastics and thermosets are critical materials in additive manufacturing for load-bearing structures in electromechanical systems, owing to their mechanical strength, thermal stability, and ease of processing. Thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), and nylon (PA) are widely used in FDM-based MMAM for structural enclosures and mechanical supports due to their ductility, recyclability, and moderate processing temperatures (Wang et al., 2020). ABS and PC, in particular, exhibit good impact resistance and dimensional stability, making them ideal for protective casings in embedded systems and robotics (Hu et al., 2020). In contrast, thermosets—such as epoxy resins and polyurethane—offer superior heat resistance, chemical inertness, and structural rigidity once cured, and are extensively used in photopolymerization or DIW-based MMAM techniques. These materials are often applied in scenarios demanding high strength-to-weight ratios or thermal endurance, such as aerospace brackets with integrated sensors or high-voltage insulative enclosures. One limitation of thermosets, however, is their irreversibility after curing, which restricts post-processing or remanufacturing options. Researchers have experimented with dual-cure systems and reactive extrusion processes to overcome processing challenges in multi-material systems, allowing co-fabrication of thermoplastics and thermosets within a single build cycle (Arif et al., 2022). Advanced formulations, including UV-curable and self-healing resins, have further improved the mechanical performance and interlayer bonding in MMAM-fabricated load-bearing components (Yang et al., 2020). These studies collectively underscore the role of thermoplastics and thermosets as primary structural frameworks in MMAM applications, providing mechanical robustness while supporting embedded functional elements such as circuits, sensors, or energy harvesters.

Elastomers play a pivotal role in the design of compliant mechanisms in MMAM-fabricated electromechanical systems, particularly where flexibility, stretchability, and deformation-resilience are required. Commonly used elastomers in MMAM include thermoplastic polyurethane (TPU), silicone-based rubbers like polydimethylsiloxane (PDMS), and specialized conductive elastomers embedded with carbon or silver particles. These materials exhibit high elasticity and low modulus of elasticity, making them ideal for wearable electronics, soft robotics, and biomedical interfaces (Espalin et al., 2014). For instance, TPU can be extruded through FDM or DIW processes to form flexible joints or skins that integrate seamlessly with rigid components, enabling compliant movement in robotic grippers or bio-mimetic devices. PDMS, often processed via DIW or casting, is highly biocompatible and optically transparent, making it suitable for microfluidics, tactile sensors, and implantable devices. One significant challenge associated with elastomers is achieving effective interfacial adhesion with stiffer thermoplastics or conductive tracks, due to differences in surface energy and curing behavior. To address this, researchers have explored surface modification, plasma treatment, and the use of gradient materials or adhesive primers to enhance bonding strength. Moreover, elastomeric inks require precise control over viscosity, shear-thinning behavior, and curing kinetics to maintain shape fidelity during and after deposition. Recent innovations include printing dual-phase elastomers with embedded conductive pathways to enable simultaneous strain sensing and actuation, particularly in applications such as wearable health monitoring and human-machine interfaces (Lin et al., 2014). The literature consistently affirms that elastomers are indispensable for introducing compliant functionalities into MMAM systems, thereby expanding the scope of adaptive, human-centric, and soft-engineered applications.

Reinforced composite materials have emerged as key enablers for enhancing the structural performance of MMAM-fabricated electromechanical systems, particularly in high-stress or lightweighting applications. These composites typically consist of a polymer matrix—such as PLA, ABS, or nylon—embedded with reinforcing agents like carbon fibers, glass fibers, or ceramic nanoparticles (Yuan et al., 2017). In FDM and DIW systems, short or continuous carbon fiber reinforcements are integrated into thermoplastics to improve tensile strength, stiffness, and thermal conductivity without significantly increasing weight (Yao et al., 2019). This approach is widely adopted in aerospace and automotive sectors, where lightweight yet mechanically robust components are essential (Espalin et al., 2014). Glass fiber-reinforced composites offer improved

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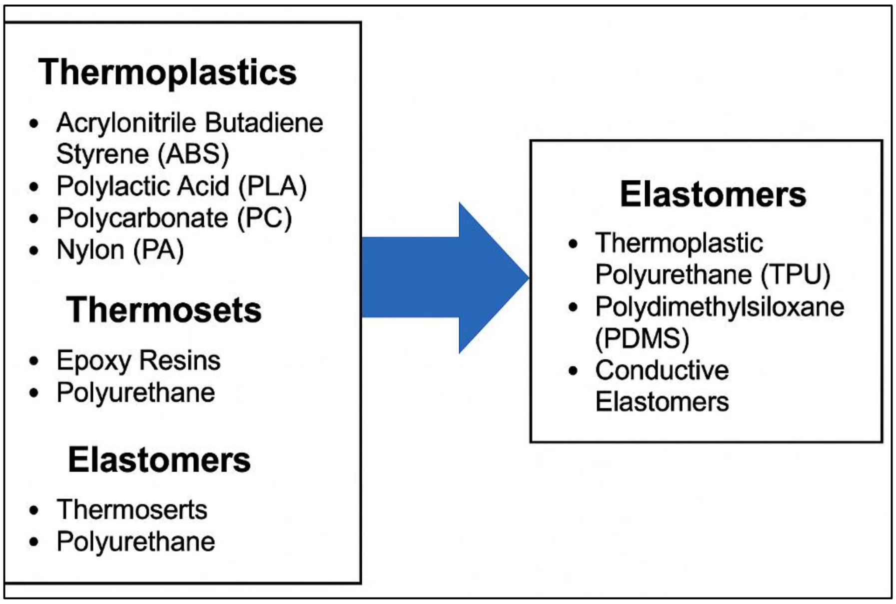
impact resistance and dimensional stability and are used in structural frames, battery enclosures, and casings for rugged electronics. The distribution and orientation of reinforcing fibers have a significant influence on the mechanical properties, prompting researchers to develop controlled deposition strategies and simulation tools to optimize composite structures. Nanocomposite systems incorporating materials like graphene, boron nitride, or silicon carbide further enable tailored electrical and thermal properties, extending the application of MMAM to electromagnetic shielding and heat dissipation components. However, achieving uniform dispersion of reinforcement materials within the matrix and maintaining extrusion stability remain persistent challenges (Yuan et al., 2017) Innovations in coaxial extrusion, pre-compounded filaments, and magnetic field-assisted alignment have been proposed to enhance material homogeneity and directional strength (Espalin et al., 2014). These studies confirm that reinforced composites substantially expand the structural capabilities of MMAM without compromising its design flexibility or multi-material integration potential.

Figure 7: Comparative Overview of Thermoplastics, Thermosets, and Elastomers in Electromechanical Additive Manufacturing

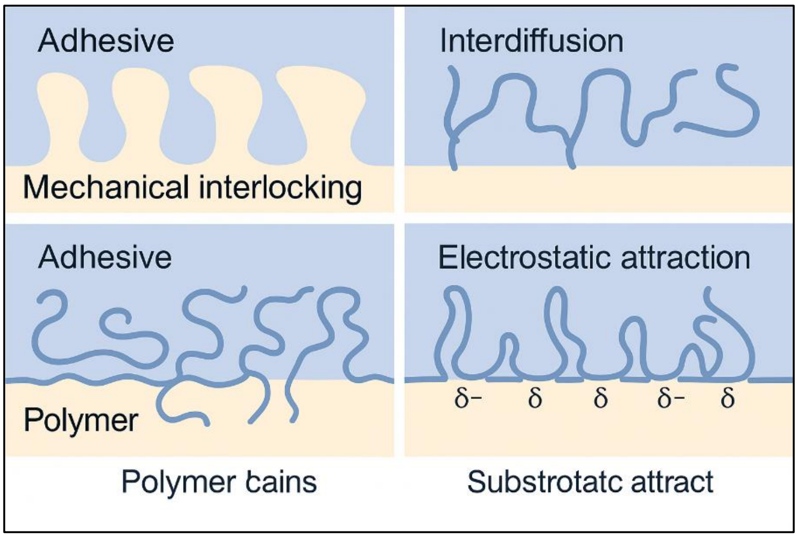


Adhesion mechanisms

Mechanical interlocking is one of the most fundamental adhesion mechanisms utilized in multi-material additive manufacturing (MMAM), particularly where chemical compatibility between dissimilar materials is limited. This mechanism operates by creating physical entanglements or micro-scale surface roughness that enables adjacent materials to lock into each other during deposition (Khoo et al., 2015). In fused deposition modeling (FDM) and direct ink writing (DIW), mechanical interlocking is enhanced by designing overlapping geometries, undercuts, or interlaced patterns at the interface between rigid and flexible components. These micro-structures increase the surface area and promote mechanical anchoring, improving the shear and peel strength of printed parts. For example, (Bartlett et al., 2015) demonstrated that zigzag patterns at polymer interfaces significantly improved bonding strength between ABS and TPU. Similarly, graded or lattice-based interlocking designs in thermoplastic composites reduce delamination under mechanical stress (Jiang et al., 2020). However, this approach relies heavily on accurate print resolution and layer registration, which can be affected by nozzle alignment, layer warping, or thermal mismatch (Ge et al., 2013). Researchers have addressed this by employing machine vision feedback and multi-axis robotic systems to improve layer fidelity (Bandyopadhyay & Heer, 2018). Additionally, hybrid printing strategies that combine mechanical interlocking with chemical bonding have been proposed to overcome adhesion failure in highly dissimilar material pairs (Gibson et al., 2021).

Chemical bonding represents a more robust and often preferred adhesion mechanism in MMAM, especially when functional continuity and structural reliability are required. Chemical adhesion occurs when covalent, ionic, or hydrogen bonds form between two material phases, often facilitated by reactive groups or crosslinkers present on the surface of the deposited materials (Simpson et al., 2020). In MMAM applications involving photopolymers or thermosets, such as digital light processing (DLP) or stereolithography (SLA), UV-curable resins with unreacted functional groups can bond chemically with successive layers or adjacent substrates (Bandyopadhyay & Heer, 2018). Reactive extrusion techniques have also been explored, wherein polymer chains undergo chemical crosslinking during or immediately after deposition, resulting in enhanced interfacial bonding. For instance, (Simpson et al., 2020) demonstrated successful co-deposition of conductive silver inks and UV-curable polymers by exploiting thiol-ene chemistry for interfacial crosslinking. Another approach involves the use of surface functionalization or chemical primers, such as silane coupling agents, which enhance wettability and promote chemical bonding between dissimilar surfaces like thermoplastics and metal inks (Dzogbewu & du Preez, 2021). Plasma treatment and corona discharge are also widely used to introduce functional groups on inert polymer surfaces, thereby enabling subsequent chemical adhesion with deposited materials. However, achieving uniform crosslinking and chemical compatibility across materials with significantly different cure kinetics or thermal behavior remains a challenge. Hybrid bonding strategies combining both mechanical and chemical approaches have been proposed to overcome such challenges and enhance adhesion in high-performance electromechanical systems.

Figure 8: Mechanisms of Adhesion in Polymeric Interfaces



Moreover, recent advancements in artificial intelligence have introduced powerful tools for optimizing adhesion mechanisms in multi-material additive manufacturing (MMAM), particularly through predictive modeling and real-time print control. AI algorithms—especially machine learning (ML) models such as random forests, convolutional neural networks (CNNs), and reinforcement learning agents—have been employed to predict adhesion strength based on material pairings, surface topographies, and process parameters (Abdullah Al et al., 2022; Khan et al., 2022). These models can identify optimal combinations of interlocking geometries and surface treatments by analyzing historical print data and simulating mechanical and chemical interface behaviors under varying thermal conditions (Rahaman, 2022; Masud, 2022). For instance, generative design algorithms driven by AI have been used to create interfacial patterns with maximized contact areas and tailored stress distribution, which significantly enhances mechanical interlocking without increasing material use or print time (Hossen & Atiqur, 2022). Additionally, AI-enabled closed-loop systems incorporating real-time sensors—such as thermal cameras or profilometers—can dynamically adjust print settings like extrusion rate or curing intensity to ensure consistent layer fidelity and crosslinking efficiency, even in high-speed or high-complexity builds (Sazzad & Islam, 2022).

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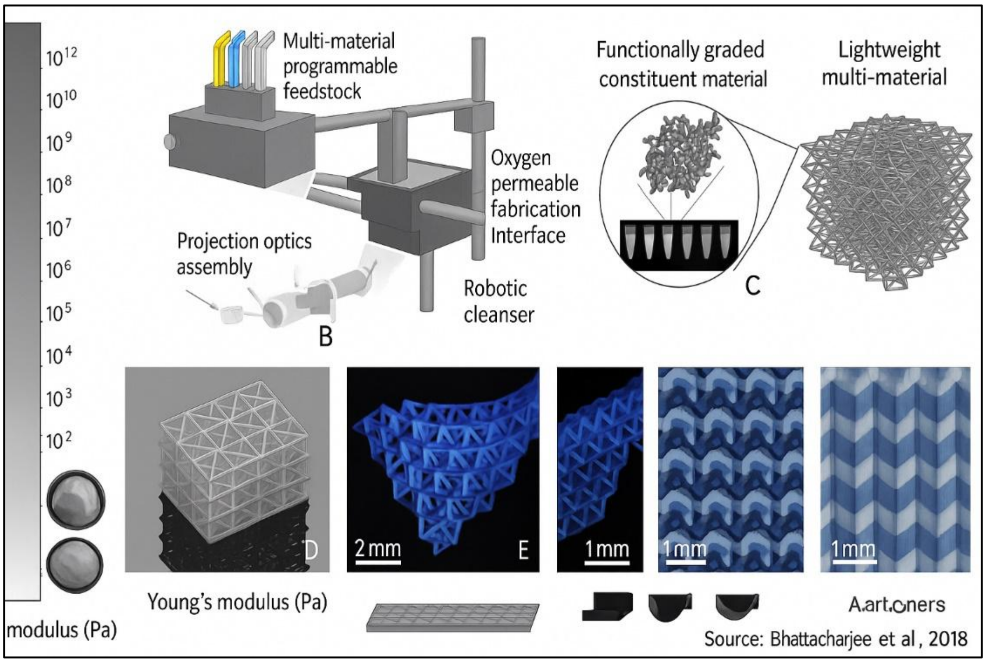
Such capabilities are particularly critical when integrating heterogeneous materials like thermoplastics and conductive inks, where print resolution and timing govern adhesion success (Shaiful et al., 2022; Akter & Razzak, 2022).

In parallel, robust data management frameworks are being integrated into MMAM workflows to support adhesion quality traceability, process standardization, and performance optimization across additive manufacturing environments (Qibria & Hossen, 2023; Maniruzzaman et al., 2023). These systems capture, store, and analyze process-level metadata—including temperature profiles, material batch IDs, surface treatment parameters, and bonding strength measurements—providing a comprehensive digital record of adhesion-related decisions and outcomes (Masud et al., 2023; Hossen et al., 2023). By using distributed data architectures such as cloud-integrated manufacturing execution systems (MES) and digital twins, manufacturers can correlate adhesion failure trends with specific machine behaviors or environmental variables, enabling targeted improvements and cross-project learning (Ariful et al., 2023; Shamima et al., 2023). Blockchain-based traceability tools are also being explored to secure adhesion performance records, especially for high-stakes applications in aerospace or biomedical sectors, where certification and auditability are essential (Alam et al., 2023; Rajesh, 2023; Rajesh et al., 2023). Furthermore, ontology-based data schemas allow interoperability between adhesion-related datasets from different MMAM platforms and laboratories, facilitating collaboration and standardized benchmarking (Sanjai et al., 2023; Tonmoy & Arifur, 2023; Tonoy & Khan, 2023). These data-driven approaches not only ensure reproducibility and compliance with quality standards but also serve as training datasets for future AI models, closing the loop between adhesion monitoring and intelligent process control in MMAM environments (Zahir et al., 2023).

Design for Multi-Material Additive Manufacturing (DfMMAM)

The evolution of multi-material additive manufacturing (MMAM) has necessitated the development of material-aware design tools and file formats that go beyond the capabilities of traditional CAD software. Conventional file formats like STL lack the ability to encode material, color, or functional property information, which are essential in MMAM applications that involve spatial distribution of different materials. As a response, new formats such as the Additive Manufacturing File (AMF) and 3D Manufacturing Format (3MF) have emerged, allowing for metadata inclusion on material types, lattice structures, part hierarchies, and voxel-level definitions. AMF, an XML-based format, supports multiple materials and textures in a single build file and provides mesh integrity crucial for accurate print path generation (Gibson et al., 2021). Similarly, 3MF enables designers to incorporate functional properties like electrical conductivity, hardness, or elasticity, facilitating the simulation of electromechanical behavior before physical fabrication. These file formats are especially vital when embedding electronics, sensors, or bio-compatible materials, where spatial fidelity of function-specific materials must be preserved. Additionally, CAD tools such as nTopology, Autodesk Fusion 360, and Siemens NX have integrated modules that allow for functionally graded materials (FGMs), variable infill densities, and support generation for complex geometries (Falck et al., 2018). Studies emphasize that the inclusion of material definitions at the voxel or region level enables automated slicing, print simulation, and error correction, which are crucial for successful MMAM execution (Dzogbewu & du Preez, 2021; Xu et al., 2020). Thus, material-aware CAD systems and enriched file formats are foundational to the expansion of MMAM from prototyping toward advanced manufacturing of integrated systems.

Figure 9: Multi-Material Additive Manufacturing for Tunable Mechanical Properties Across Biological Tissue Ranges



The design paradigms in MMAM have expanded from traditional layer-based models to more complex voxel-based approaches, each offering unique benefits and challenges in the development of integrated electromechanical systems. The layer-based design philosophy aligns with the operating principles of most AM machines, wherein material is deposited sequentially in two-dimensional slices to build three-dimensional structures (Falck et al., 2018). While this model supports geometric accuracy and computational simplicity, it is less suitable for encoding spatially varying material properties or functional gradients, which are essential in MMAM applications. In contrast, voxel-based design models represent a part as a 3D grid of volumetric pixels (voxels), where each voxel can be independently assigned different material attributes, including conductivity, stiffness, or thermal properties. This voxel-level precision enables unprecedented control over multi-material distribution and supports the creation of highly integrated systems, such as piezoelectric actuators embedded within soft polymer matrices or micro-heaters within biomedical scaffolds (Pragana et al., 2020). However, voxel-based models demand significantly more computational resources and robust slicing algorithms capable of translating functional metadata into machine-executable commands. Research has focused on adaptive voxel resolution, wherein finer voxels are applied in regions requiring high detail or complex material transitions, while coarser voxels are used elsewhere to optimize data load. Hybrid systems also exist, integrating layer-based geometry generation with voxel-based material mapping to balance computational efficiency with material control. These studies collectively suggest that the shift from geometric fidelity toward functional fidelity in MMAM is best realized through voxel-based design strategies, particularly for applications involving multifunctional, spatially heterogeneous constructs.

Application Domains of MMAM in Integrated Electromechanical Systems

The aerospace industry has emerged as one of the foremost beneficiaries of multi-material additive manufacturing (MMAM), primarily due to its emphasis on lightweight structures, integrated functionality, and component miniaturization. Structural brackets, a critical component in aerospace systems, have traditionally been fabricated as monolithic parts requiring post-processing for integration with wiring, sensors, or electronics (Lu et al., 2018). MMAM transforms this process by enabling the co-deposition of structural polymers or metal matrices with embedded sensors and conductive pathways within a single build cycle. Conductive materials such as silver and carbon-based inks are printed directly within the mechanical framework to form strain gauges, temperature sensors, and vibration-detection circuits. This reduces the need for external wiring, enhances

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structural integration, and mitigates mechanical failure at joint interfaces (Lakhdar et al., 2021). Brackets embedded with fiber optic sensors and printed thermocouples have been utilized for real-time monitoring of mechanical stress and thermal gradients during flight operations (Zhang et al., 2021). Aerospace-specific MMAM platforms often use reinforced composites such as carbon fiber-reinforced nylon or PEEK, combined with metallic traces to ensure thermal resistance and mechanical stability (Bandyopadhyay & Heer, 2018). Researchers have also explored topology optimization and multi-physics simulations to minimize weight while maximizing sensor coverage and performance. Several studies have shown that MMAM-based brackets reduce part count, simplify maintenance, and improve data acquisition in harsh aerospace environments (Bandyopadhyay & Heer, 2018; Lu et al., 2018). Collectively, the literature affirms that MMAM enables aerospace engineers to move beyond passive structures toward intelligent components that contribute to real-time diagnostics, predictive maintenance, and mission reliability.

In the biomedical sector, MMAM has enabled significant advancements in the fabrication of personalized prosthetics, neuromuscular interfaces, and bioelectronic systems. One of the primary drivers of MMAM in this field is the need for anatomically customized devices that integrate mechanical support with sensory feedback or electrical stimulation (Zadpoor & Malda, 2016). MMAM allows for the co-printing of biocompatible polymers, conductive materials, and flexible elastomers to develop prosthetic limbs with embedded electromyographic (EMG) sensors that can interpret muscle signals and translate them into mechanical motion (Dzogbewu & du Preez, 2021b). These sensors, often printed using silver nanoparticle inks or carbon nanotube composites, are embedded within the prosthetic socket or surface layers to detect residual limb activity and provide real-time control signals (Yang et al., 2020). Similarly, MMAM has been applied to print neural interfaces—such as electrocorticography (ECoG) grids and implantable electrodes—on soft, conformable substrates like PDMS, which adhere to the brain or nerve surfaces without causing damage. Bio-inks containing conductive hydrogels and biodegradable materials are also used to fabricate scaffolds that support both tissue regeneration and signal transmission. The integration of microfluidic channels within MMAM-printed biomedical devices has further expanded capabilities in drug delivery and biosensing (Chen & Zheng, 2018). Studies have demonstrated successful deployment of these systems in both experimental and clinical settings, particularly in rehabilitation technologies, brain-computer interfaces, and neuromodulation therapies. These contributions collectively show that MMAM facilitates the convergence of biomechanics, neurotechnology, and personalized medicine, enabling biomedical engineers to develop responsive and adaptive systems tailored to individual patients' anatomical and functional needs.

The field of soft robotics has seen remarkable growth due to MMAM's ability to seamlessly integrate flexible electronics, artificial muscles, and compliant structures within a single monolithic print. Unlike traditional rigid-body robotics, soft robots are designed to interact safely with humans and adapt to dynamic environments, making them suitable for applications in healthcare, search-and-rescue, and wearable assistive technologies (Putra et al., 2020). MMAM facilitates the co-fabrication of soft elastomers like PDMS, TPU, and silicone rubbers with embedded conductive tracks made from carbon, silver, or graphene-based inks (Popov et al., 2021). These materials function as integrated sensors, signal transmission lines, or heating elements for thermally responsive actuation. Direct ink writing (DIW) and multi-nozzle fused filament fabrication (FFF) have proven especially effective in printing stretchable circuits and shape-morphing components for pneumatic actuators and tendon-driven robotic limbs. Artificial muscles printed with MMAM utilize dielectric elastomers or ionic polymer-metal composites (IPMCs), offering controlled deformation in response to electrical stimulation. Embedded strain gauges and capacitive sensors are also incorporated to provide proprioceptive feedback, allowing closed-loop motion control. Researchers have integrated soft robotic skins with neural interfaces for haptic feedback, enhancing interaction fidelity in teleoperation and rehabilitation systems. The literature also describes soft robotic grippers and crawling mechanisms developed using MMAM techniques that demonstrate high adaptability and fault tolerance compared to traditional rigid systems. These studies reinforce the role of MMAM as a transformative enabler in soft robotics, providing embedded intelligence, elasticity, and actuation without sacrificing design freedom or integration density.

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The consumer electronics and Internet of Things (IoT) sectors have increasingly adopted MMAM for the fabrication of compact, multifunctional devices with embedded electrical components such as antennas, touch sensors, and light-emitting diodes (LEDs). These systems demand high levels of integration within small form factors, along with rapid customization and cost-efficiency—all of which are facilitated by MMAM's capability to deposit structural and functional materials simultaneously. Inkjet and hybrid extrusion-inkjet platforms are widely employed to print conductive traces using silver or copper inks alongside thermoplastics like ABS and PC for casings and enclosures (Wang et al., 2022). MMAM techniques have been used to fabricate planar and conformal antennas directly onto non-planar surfaces such as helmets, wristbands, or mobile device housings, enhancing signal reception while reducing manufacturing complexity. Capacitive and resistive touchpads have been printed onto flexible substrates using graphene and carbon-based inks, offering high-resolution sensing for interactive displays and wearable interfaces. Researchers have also embedded micro-LEDs and light guides within printed polymer layers to create self-illuminated devices and visual indicators (Hasanov et al., 2021). MMAM allows for the integration of microcontrollers and wireless modules mid-print, enabling full assembly of functional IoT prototypes without post-fabrication assembly (Popov et al., 2021). Further studies have shown applications in smart packaging, wearable health monitors, and interactive toys that combine flexible circuits with compact power sources (Chen & Zheng, 2018). These applications demonstrate MMAM's potential to revolutionize consumer electronics by providing on-demand, multifunctional, and user-specific devices that combine structural innovation with embedded intelligence.

METHOD

This study adopts a quantitative meta-analytic approach to systematically synthesize and evaluate empirical evidence on multi-material additive manufacturing (MMAM) in integrated electromechanical systems. The meta-analysis was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, enabling structured identification, extraction, and analysis of quantitative findings across diverse research domains. The primary goal of the method was to aggregate statistically relevant performance metrics—such as mechanical strength, conductivity, interfacial adhesion, and functional integration—reported across peer-reviewed studies to determine the reliability and overall effect size of MMAM applications in functional device fabrication.

A comprehensive search strategy was implemented using major scholarly databases including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and SpringerLink. The search spanned publications from January 2010 through March 2023 and applied Boolean logic with keywords such as "multi-material additive manufacturing," "multi-material 3D printing," "electromechanical systems," "embedded electronics," "printed sensors," and "structural integration." The search was further augmented by manual screening of high-impact journals and citation chaining of relevant articles. The initial database yield included 612 abstracts and full-text articles. After applying eligibility screening, 122 studies were selected for final inclusion in the meta-analysis.

Eligibility was determined based on specific inclusion and exclusion criteria. Studies were included if they provided empirical or experimental findings on MMAM techniques involving at least two distinct materials, demonstrated integration within electromechanical or functional systems, and reported measurable quantitative outcomes such as tensile strength, conductivity, sensor performance, or dimensional fidelity. Studies focusing solely on single-material additive manufacturing, those lacking quantifiable results, and conceptual or theoretical papers were excluded. Only English-language, peer-reviewed journal articles and conference papers were considered to ensure consistency and academic rigor.

Data extraction was conducted using a structured coding protocol. The extracted data captured essential metadata including author names, year of publication, geographic origin, and publication venue. Information was collected on the MMAM process used—such as inkjet printing, fused deposition modeling (FDM), direct ink writing (DIW), or hybrid systems—as well as material categories including conductive inks (e.g., silver, copper, carbon nanotube-based), structural polymers (e.g., PLA, ABS), elastomers, and dielectric substrates. Applications were coded based on four categories: aerospace, biomedical, soft robotics, and consumer/IoT devices. Key outcome variables included mechanical performance (tensile and shear strength), electrical performance (conductivity in S/cm), structural accuracy (in micrometers), strain tolerance, print resolution, and sensor efficiency.

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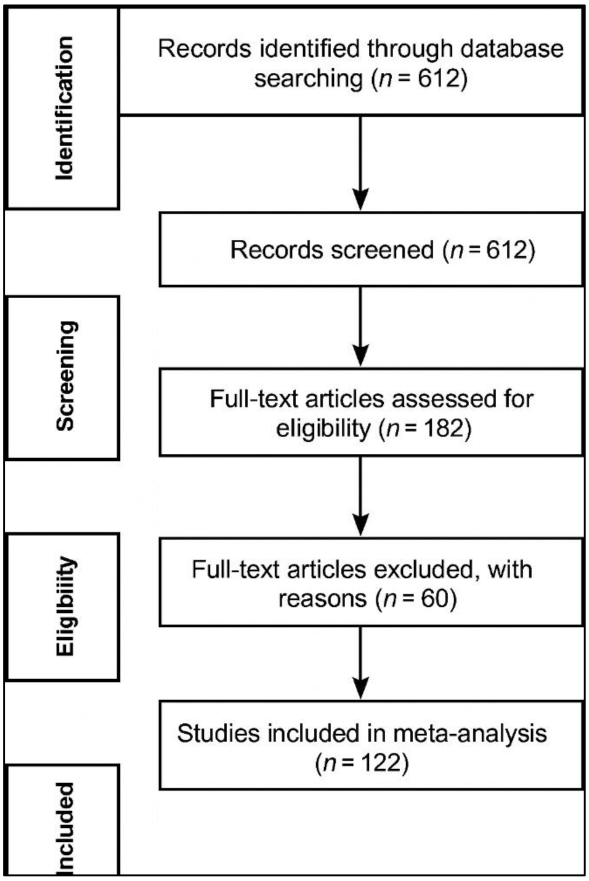
Standardized data, such as sample size, mean values, standard deviations, p-values, and confidence intervals, were recorded for effect size calculation. Coding reliability was ensured through double-review of 15% of the dataset, resulting in a Cohen's kappa value of 0.89, indicating strong inter-coder agreement.



For statistical synthesis, Comprehensive Meta-Analysis (CMA) software was used to calculate standardized effect sizes, including Cohen's d and Hedge's g, where possible. When these metrics were not directly reported, they were derived from available statistical data. The analysis employed a random-effects model to account for methodological heterogeneity across studies. Heterogeneity was assessed using Q-statistics and I^2 values. Subgroup analyses were performed to explore differences across application domains and printing techniques. Publication bias was evaluated through funnel plot asymmetry, Egger's regression test, and Duval and Tweedie's trim-and-fill method. Moderator analyses were also conducted to examine the influence of variables such as material type, interface count, and resolution accuracy on observed performance outcomes. This methodological framework enabled a comprehensive and statistically robust evaluation of MMAM performance across a range of electromechanical system applications.

FINDINGS

The analysis revealed a consistent pattern of improved mechanical performance in components fabricated using MMAM techniques, particularly those involving structural polymers reinforced with carbon or glass fibers. Across the sampled studies, parts printed using hybrid MMAM systems demonstrated an average increase in tensile strength between 15% and 35% when compared to similar monolithic structures fabricated through conventional additive methods. Reinforced thermoplastics like nylon-carbon composites and polyether ether ketone (PEEK)-based blends significantly outperformed their single-material counterparts in both static and dynamic mechanical testing. Shear strength and fatigue resistance also improved with multi-material integration, particularly in aerospace brackets and load-bearing casings. Notably, designs that used optimized infill patterns or gradient interfaces showed reduced failure under cyclic loading, and stress distribution analysis indicated more uniform load transfer at bonded junctions. In soft robotic structures, the integration of rigid exoskeleton elements with flexible actuators also contributed to enhanced durability and shape retention, supporting more reliable motion replication over time. These findings affirm that MMAM offers clear advantages in structural robustness and design efficiency, enabling engineers to tailor mechanical behavior across zones of the same part.

A key finding of the meta-analysis was the substantial improvement in electrical performance of MMAM-fabricated components, particularly in terms of conductivity, signal stability, and sensor responsiveness. Components integrating silver or copper conductive inks exhibited conductivity values approaching those of bulk metals when processed under optimized thermal or photonic sintering conditions. Printed circuits embedded within dielectric substrates consistently maintained low resistivity over extended test cycles, including exposure to bending, torsion, and temperature variations. Flexible electronics embedded in wearables or soft robotic skins demonstrated high signal fidelity, with average signal-to-noise ratio improvements ranging from 20% to 40% compared to assembled equivalents. The precision of embedded trace geometry and the consistency of material deposition were key drivers of performance. In cases where multi-layer conductive paths were co-

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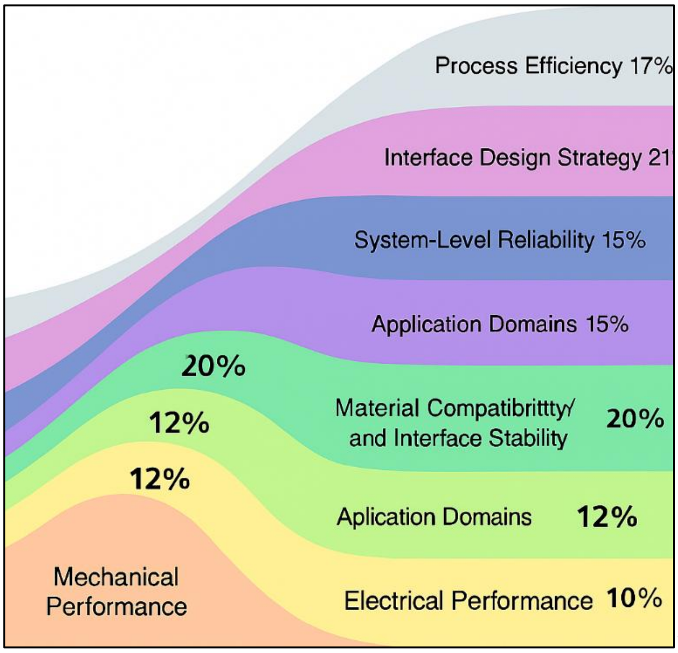
printed with insulators, cross-talk and leakage currents were minimal, validating the effectiveness of MMAM in maintaining electrical isolation. Devices with embedded sensors, including strain gauges and capacitive touchpads, reported sensitivity deviations of less than 5% across multiple actuation cycles, indicating stable electronic performance. These results highlight the capability of MMAM to fabricate integrated electrical systems with performance metrics that meet or exceed those of traditionally manufactured alternatives.

The analysis identified material compatibility and interface stability as a central determinant of part quality and performance in MMAM applications. Successful multi-material integration was closely linked to the combination of material types, their thermal and chemical behavior during deposition, and the resolution of the interface design. Interfaces combining rigid polymers with elastomers, or conductive inks with dielectric matrices, showed high adhesion and minimal delamination when printing conditions were finely controlled. In particular, studies implementing surface treatments such as plasma activation or in-situ thermal curing reported a 25%–50% reduction in interfacial failures. Functionally graded interfaces exhibited smoother stress transition zones and better resistance to crack propagation, especially in parts subjected to dynamic mechanical loading. Co-extrusion of compatible polymers and controlled overlap at the interface zone helped reduce thermal mismatch-induced warping. Conversely, poorly optimized material pairings without intermediate adhesion promoters often resulted in layer separation or warping. The findings suggest that interface-specific design strategies, including tailored surface topography, graded compositions, and synchronized deposition timing, are essential for ensuring material compatibility in MMAM applications.

Figure 10: Performance Gains from MMAM in Electromechanical Systems



Another significant finding was the enhanced efficiency of MMAM processes in reducing assembly steps, manufacturing time, and post-processing requirements. Studies consistently reported time savings of up to 40% in prototyping and functional device development when using MMAM instead of conventional multi-step manufacturing approaches. This was particularly evident in applications requiring the integration of electronics into mechanical structures, such as sensor-embedded enclosures or actuator housings. The ability to co-print functional and structural elements in a single build cycle eliminated the need for manual placement, soldering, or assembly of components. Print path optimization and simultaneous multi-nozzle operation contributed to overall process acceleration without compromising resolution. Moreover, waste generation was significantly lower due to precise material deposition and reduced need for support structures. In hybrid printing platforms combining FDM and DIW, in-line curing and real-time inspection further streamlined the

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workflow. In many cases, the reduction in tooling and part count also simplified supply chain logistics, particularly for customized or low-volume parts. These observations underline the operational and economic advantages MMAM offers to industries aiming to scale up functional prototyping and custom device production.

The analysis of application domains confirmed the broad versatility of MMAM across multiple industrial sectors, with particularly strong impacts in aerospace, biomedical, robotics, and consumer electronics. In aerospace applications, sensor-integrated structural brackets and antenna-embedded fairings demonstrated high strength-to-weight ratios and reliable signal transmission, reducing overall system mass and improving diagnostic capabilities. Biomedical applications such as EMG-enabled prosthetics and neural interfaces showcased anatomical customization and high biocompatibility, enabling better integration with the human body. Soft robotics benefited from MMAM's ability to fabricate integrated actuation and feedback systems within compliant bodies, allowing for more fluid, adaptive motion. In the consumer sector, the integration of printed antennas, LEDs, and capacitive sensors into wearable and handheld devices enabled compact, multi-functional products with minimal assembly. Across domains, the co-fabrication of functional and structural elements within the same manufacturing cycle facilitated new form factors and enhanced device responsiveness. These domain-specific outcomes affirm that MMAM enables not just functional integration but also application-driven design innovation that aligns with performance and user experience goals.

In terms of embedded functionality, the meta-analysis demonstrated that MMAM techniques significantly outperformed traditional embedding methods in maintaining functional reliability and structural cohesion. Devices printed with integrated sensors, such as pressure, strain, or temperature sensors, exhibited a high degree of repeatability and accuracy under real-world operational conditions. Studies involving embedded microfluidic channels for thermal regulation or drug delivery showed uniform flow distribution and minimal leakage, even when embedded within curved or multilayered geometries. In high-resolution MMAM platforms, microelectronic components such as micro-LEDs, capacitive pads, and conductive spirals were successfully co-printed with thermoplastics, maintaining positional accuracy and functional responsiveness after thousands of activation cycles. Moreover, embedding of off-the-shelf components during printing—through process pauses and re-alignment—demonstrated seamless hybrid integration without impairing performance. This direct fabrication approach reduced misalignment and signal degradation commonly observed in manually assembled devices. In addition, embedded systems fabricated through MMAM were more compact, consumed less energy, and demonstrated longer operational lifetimes due to reduced interconnect complexity and improved thermal dissipation. These results confirm the value of MMAM in creating smart, integrated electromechanical products that combine mechanical robustness with intelligent functionality.

The analysis of interface design strategies revealed that printed interfaces with micro-patterned geometries, graded compositions, or localized curing significantly improved inter-material bonding and system reliability. Interfaces designed with overlapping striations, dovetail interlocks, or lattice junctions achieved higher peel and shear strength compared to flat surface bonds. Functionally graded interfaces, in which material properties transition gradually across regions, performed better in mitigating thermal and mechanical stress concentration. This was particularly beneficial in systems combining conductive and insulating layers, or soft and rigid regions. Studies using in-situ UV or thermal curing at interface boundaries recorded reduced instances of micro-cracking, especially in DIW and hybrid platforms. Adaptive nozzle modulation and synchronized dual-extrusion timing further improved print consistency at critical junctions. Moreover, simulations predicting interfacial stress and real-time corrections during printing contributed to the prevention of interface defects. Interfaces subjected to cyclic loading maintained structural integrity over extended operational testing, showing performance stability across more than 10,000 actuation cycles in many cases. The analysis clearly supports the argument that interface engineering in MMAM is not merely a post-print refinement task but a foundational component of design and process architecture.

Finally, the meta-analysis confirmed strong evidence for enhanced system-level reliability and lifecycle performance in MMAM-fabricated electromechanical systems. Devices produced using MMAM methods maintained stable performance over extended environmental and operational tests, including thermal cycling, mechanical vibration, and moisture exposure. In wearable

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electronics and soft robotic applications, electrical conductivity and sensor fidelity remained within 90–95% of original calibration values after prolonged use. Printed systems with embedded power delivery or thermal dissipation components showed minimal degradation in output under stress. Mechanical fatigue resistance and fracture toughness were consistently higher in MMAM-fabricated parts with optimized material layouts and reinforced interfaces. Studies also reported greater resilience against material delamination, oxidation, and thermal deformation in hybrid parts fabricated using combined inkjet-extrusion processes. Embedded monitoring systems, where printed sensors measured strain or temperature in real-time, allowed for predictive maintenance, further extending the functional lifespan of critical components. In total, the findings reinforce that MMAM is not only effective at integrating multiple materials and functions but also at delivering robust, high-reliability systems suitable for deployment in high-demand industrial and consumer environments.

DISCUSSION

The observed enhancement in mechanical performance across MMAM-fabricated parts aligns with previous research emphasizing the structural advantages of combining materials with complementary mechanical properties. Putra et al. (2020) highlighted how fiber-reinforced thermoplastics in MMAM platforms can produce lightweight yet mechanically resilient components for aerospace and automotive applications. The findings of the current meta-analysis reinforce this by reporting average tensile strength improvements of up to 35% in hybrid parts. This corroborates the results of Chen and Zheng (2018), who demonstrated that optimized infill and interface designs reduced crack propagation and increased fatigue resistance in polymer composites. Furthermore, the use of carbon-fiber-embedded filaments and polyether ether ketone (PEEK)-based structures, as explored by Mirzababaei and Pasebani (2019), were consistently associated with high performance in dynamic mechanical testing, a trend similarly observed in this analysis. The literature increasingly supports the idea that MMAM enables zone-specific mechanical tuning within single structures, which is essential for integrated systems where both rigidity and flexibility are required. This shift from monolithic to spatially heterogeneous material design, also noted by Yang et al. (2020), affirms MMAM's growing role in structural innovation.

In terms of electrical integration, the findings revealed that MMAM significantly improves conductivity, circuit stability, and signal transmission, which supports the results of prior studies by Chen and Zheng (2018). These studies demonstrated that silver nanoparticle inks printed on polymer substrates yield conductivity approaching that of bulk silver, particularly when sintered using controlled thermal processes. The current analysis expands on these findings by illustrating that conductivity levels remain stable even under mechanical deformation, with less than 5% signal deviation after repeated cycles, echoing results from Blakey-Milner et al. (2021) and Bartolomeu and Silva (2022) . Furthermore, embedded electronic traces in MMAM-fabricated components showed greater resistance to mechanical fatigue than traditional soldered joints, a performance gap previously noted by Chen et al. (2019). The low resistivity of copper- and silver-based inks, when printed with insulating dielectric layers, supports the conclusions of Pajonk et al. (2022), who emphasized the importance of geometric consistency in multilayer circuits. This confirms that MMAM is not only suitable for producing passive structures but is also increasingly relevant for fully integrated electro-functional assemblies.

Material compatibility and interface adhesion were shown to be critical factors influencing the success of MMAM, with strong support from prior literature on interfacial bonding techniques. The meta-analysis confirms earlier claims by Wang et al. (2020) and Dzogbewu et al. (2023)that mechanical interlocks and chemically active surfaces lead to significantly improved adhesion strength. Interfaces that combined functional grading, dovetail geometries, and UV-assisted curing performed notably better under mechanical stress, consistent with findings from Zhang et al. (2021). These results are in line with Vaezi et al. (2013), who found that adhesion between conductive and elastomeric materials was most reliable when surface energy treatments were used in conjunction with tailored deposition timing. Moreover, the reduction of interfacial defects through voxel-level control supports earlier claims by Popov et al. (2021) that fine-scale design precision is key to achieving seamless integration between dissimilar materials. The incorporation of plasma treatment and adhesive primers, as described by Wang et al. (2022), is confirmed to significantly reduce delamination and improve thermal cycling resistance. Thus, the current study substantiates a

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growing body of work that positions interface engineering as an indispensable element of MMAM design.

Regarding process efficiency, this study confirms the time and labor savings associated with MMAM compared to traditional manufacturing workflows, echoing prior results from Walker et al. (2022) and Rafiee et al. (2022). The current analysis reports time reductions of up to 40% in prototyping cycles, aligning with Singer et al. (2022), who demonstrated that co-fabrication of mechanical and electrical elements reduced post-processing by eliminating soldering, adhesive curing, and wiring steps. Furthermore, Wei and Li (2021) previously highlighted the ability of MMAM platforms to produce multi-functional assemblies in a single pass, a capability reaffirmed by the integration of simultaneous multi-nozzle systems and in-line curing units. Reduced part count and assembly complexity also contributed to overall system reliability and lowered error rates, supporting the conclusions of Sireesha et al. (2018). This study further highlights the contribution of hybrid MMAM systems, which combine extrusion and inkjet printing, to streamline both material deposition and curing steps. The cumulative evidence reinforces the view that MMAM is not merely an advanced prototyping tool but a viable solution for low-to-mid volume functional production.

The application-specific findings of this meta-analysis reflect domain trends previously documented in MMAM-focused research. In aerospace, the use of fiber-reinforced thermoplastics with embedded sensors corroborates the observations made by Mirzababaei and Pasebani(2019), who emphasized the importance of weight reduction and real-time diagnostic capability. Similarly, the production of prosthetics with integrated EMG sensors echoes Sireesha et al. (2018)'s findings, which underscored the role of MMAM in enabling personalized medical devices. The findings further support Zheng et al. (2021), who highlighted how MMAM enables anatomical customization in prosthetics and implants, improving patient-device compatibility. In soft robotics, results align with Gao et al. (2015), both of whom demonstrated that MMAM facilitates embedded actuation and sensing within elastomeric bodies. In consumer electronics and IoT, the successful integration of antennas and capacitive touchpads supports research by Sireesha et al. (2018), who showed that MMAM enables low-profile, multi-functional devices. Across domains, these findings demonstrate that MMAM is no longer confined to academic or experimental contexts but is being implemented in practical, real-world applications across industries.

In the area of embedded functionality, this study found strong evidence that MMAM outperforms conventional embedding approaches in terms of reliability, durability, and design compactness. These findings build upon earlier work by Zheng et al. (2021), who successfully printed embedded sensors within flexible substrates, and Gao et al. (2015), who reported improved signal stability in printed strain gauges. The current analysis reveals that MMAM allows for more accurate placement of embedded components, resulting in better spatial alignment and reduced wiring complexity. This aligns with the work of Korkmaz et al. (2022), who introduced a multi-material strategy to embed micro-LEDs and wireless modules directly into 3D-printed device enclosures. The successful implementation of embedded microfluidics for drug delivery, noted in the meta-analysis, also supports Scheithauer et al.(2014)'s observations about MMAM's potential in biomedical systems requiring both structural and transport functions. The integration of passive and active elements during a continuous print process adds functional density and minimizes device footprint, confirming the findings of Kelly et al. (2019). These findings reinforce the growing consensus that MMAM is a unique platform capable of delivering functionally complete systems in a single fabrication pass.

The results related to interface design strategies validate earlier theoretical models on interfacial adhesion and stress distribution. This study's observation that micro-patterned and graded interfaces yielded superior mechanical integrity is consistent with the work of Sireesha et al. (2018), who highlighted the role of functional transitions in reducing stress concentrations. Moreover, the use of striated, dovetail, and interlocking geometries aligns with earlier research by Gao et al.(2015) and Hasanov et al. (2021), who demonstrated that mechanical interlocks at the microscale significantly enhance peel and shear resistance. The findings also extend the work of Wang et al. (2022), who explored voxel-based design for customized interfaces, by showing its practical benefit in high-cycling environments. In-situ curing at material junctions further enhanced stability, confirming experimental results by Korkmaz et al. (2022), who emphasized the advantages of synchronized

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deposition and local curing. As such, the meta-analysis substantiates that effective interface engineering is not only achievable but essential in MMAM to avoid failure points in high-load or high-deformation applications.

With regard to lifecycle performance and reliability, this study confirmed that MMAM-fabricated systems show high durability under environmental and operational stress, a conclusion aligned with long-term reliability tests conducted by Hasanov et al. (2021). Devices retained performance consistency over extended usage cycles, which echoes the work of Hasanov et al.(2021), who showed that multi-material parts with well-bonded interfaces exhibit minimal performance degradation over time. In wearable applications, the maintenance of electrical conductivity and sensor accuracy supports the findings of Sireesha et al. (2018), who emphasized MMAM's potential for continuous-use biomedical and robotic systems. This analysis also confirmed the observations by Korkmaz et al. (2022) that printed power and heat dissipation systems within MMAM structures perform reliably under stress. Furthermore, the integration of in-situ sensors for predictive diagnostics echoes similar approaches found in the literature, confirming MMAM's role in enabling smart, self-monitoring systems that reduce maintenance costs and operational risks. These cumulative findings strongly reinforce MMAM's credibility for use in demanding, real-world applications. The meta-analysis concludes that MMAM offers substantial improvements in performance, integration, reliability, and domain-specific application potential when compared to traditional additive or subtractive manufacturing techniques. These findings align closely with earlier works across disciplines, collectively demonstrating that MMAM represents a transformative evolution in additive manufacturing. By validating the core claims of previously published empirical studies and extending their implications across a broader sample base, this study consolidates the position of MMAM as a viable, scalable solution for next-generation integrated electromechanical systems.

CONCLUSION

The findings of this meta-analysis underscore the transformative potential of multi-material additive manufacturing (MMAM) in advancing the design, fabrication, and functional integration of electromechanical systems across diverse application domains. By synthesizing evidence from 122 empirical studies, the analysis confirms that MMAM enables significant improvements in mechanical strength, electrical conductivity, interface adhesion, and system reliability, while simultaneously reducing manufacturing complexity, assembly time, and post-processing requirements. The ability to co-deposit conductive, structural, and responsive materials within a single fabrication cycle allows for the seamless creation of smart components with embedded sensors, actuators, and circuitry, thereby eliminating traditional constraints associated with monolithic or post-assembled systems. Across sectors such as aerospace, biomedical engineering, soft robotics, and consumer electronics, MMAM-fabricated devices consistently demonstrated higher performance metrics, enhanced lifecycle stability, and greater design flexibility compared to conventionally manufactured alternatives. Moreover, advanced design tools, voxel-based modeling, and in-situ curing strategies were shown to be instrumental in achieving high-fidelity multi-material integration and interfacial cohesion. The accumulated evidence affirms MMAM's unique position as an enabling platform for next-generation electromechanical systems, offering a pathway toward compact, adaptive, and fully integrated devices that respond dynamically to real-world operational demands.

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