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Review

Strategic Implementation of Multimaterial Additive Manufacturing: Bridging Research and Real-World Applications

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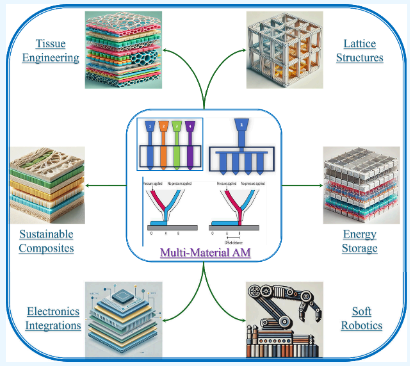
ABSTRACT: The single-material additive manufacturing revolution has accelerated innovation in the manufacturing field, enabling the combination of multiple materials in one operation using additives of metals, ceramics, and polymers. Although still in its infancy, researchers are adopting this strategy, indicating a shift from research and development to practical applications. By aggregating numerous materials with different properties concurrently, the multimaterial additive manufacturing approach entitles the simplest fabrication of multifunctional systems and devices. A review focuses on the opportunities and challenges presented by the trend toward recent advancements in the multinozzle system. Multinozzle 3D printing has great applications in bioprinting and tissue engineering, electronics integration, and civil/structural engineering. This review highlights the exciting opportunities and challenges that come with it. Additionally, this review showcases the recent advancements in the multinozzle system that have made it a promising solution in this field.



1. INTRODUCTION

The industries and economies are rapidly developing, requiring large-scale fabrication of complex materials with low cost, high quality, and efficiency to maintain competitive innovation in the market. These hurdles have led to new perspectives and techniques for manufacturing.[1−3] Modern Additive manufacturing (AM) is a cutting-edge technology developed to accelerate the integration of smart materials and advanced printing to add new forms of complexity through multifunctionality and characteristics. The first multimaterial 3D printer was Fab@Home, and it was introduced in 2006.[4] In addition to being used to fabricate active batteries, actuators, and sensors directly, they are also produced using.[5−8] The most structured technique for manufacturing multimaterial composites is Multi-Material Additive Manufacturing (MMAM), with advantages for the automotive, medical, and aerospace sectors. Depending on the technology, feedstock, energy supply, and build volume, the systems of multimaterial additive manufacturing are feasible and categorized into seven distinct groups as defined in ISO/ASTM 52900: Directed Energy Deposition, photopolymerization, Material Extrusion, Binder Jetting, Powder Bed Fusion, Material jetting, and Sheet Lamination.[9−11] The classification of AM methods based on ISO/ASTM 529000:2015, which used single feed material for AM, is portrayed in Figure 1. Numerous additive manufacturing (AM) techniques are utilized to create multimaterial products from diverse materials such as polymers, metals, ceramics, and biomaterials.[12,13] Nozzles are a vital part of the recent breakthrough technology because it gives a finer product. The 3D printing capabilities are restricted by using only one extruder in which a single filament of color or substance can only be loaded into an extruder at a time. A delay in the printing process would be necessary to change the filament, which would take some time to complete. The procedure includes emptying the utilized filament, wiping down the extruder chamber, and inserting the renewal filament. A versatile, affordable, multimaterial, vision-based 3D printing platform constructed with extreme precision has recently pushed the use of multinozzle extruder systems.[14−17] Recent developments have been made for multimaterial component printing with geometrically changing properties.[16,18−20] Multinozzle additive manufacturing is advancing, enabling more intricate multimaterial combinations, composite gradients with active elements, and achieving previously impractical multifunctionality. A multinozzle, multimaterial printing system can handle a wide variety of material viscosities from 0 to 1000 cP. It is designed to accommodate diverse material properties, making it the ideal choice for any printing need[21,22] This technical field has undergone remarkable

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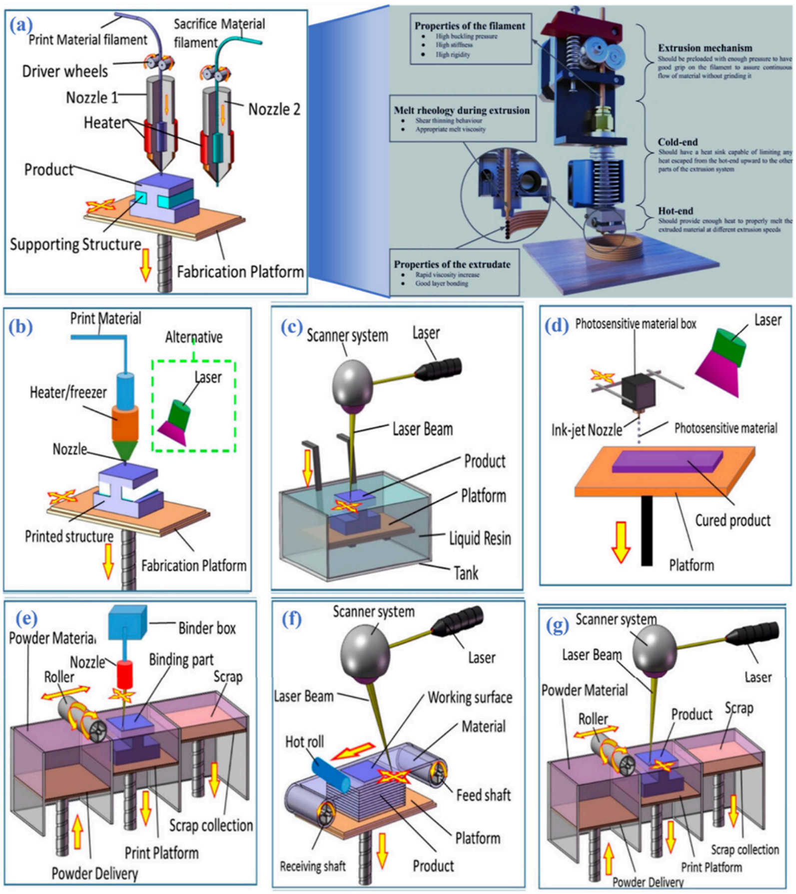

Figure 1. Graphic representation of a classification of additive manufacturing based on ISO/ASTM 529000:2015: (a) extrusion-based FDM with its features and proper extrusion, (b) extrusion-based DIW process, (c) SLA method of liquid resin, (d) photopolymerization in Polyjet, (e) 3D modeling via binder jetting, (f) sheet lamination process (LOM), and (g) method of SLM and SLS. Reused from refs 28 and 29 with permission: Copyright 2017, MDPI, and Copyright 2021, Springer Nature.

developments in design, computation, characterization methods, and material science, leading to significant advancements in expertise.[23] The developed multimaterial 3D food printing methodology enables seamless fabrication without nozzle switching, mitigating filament fragmentation and ensuring structural consistency. Addressing the rheological challenges posed by diverse food inks, particularly their yield stress, the study optimizes flow resistance by tailoring nozzle channel diameters, effectively preventing backflow and preserving print integrity. The Y-junction nozzle design facilitates the controlled deposition of two distinct food materials, with an enhanced transition achieved when the outlet diameter exceeds that of the inner channels. This approach is scalable, allowing additional inlets to modulate aesthetics, texture, and flavor, broadening applications in personalized nutrition and culinary innovation. Furthermore, the integration of edible QR codes introduces interactive food experiences, enabling digital information retrieval through consumption. Beyond gastronomy, the methodology holds promise for fabrication, accommodating multiple bio inks with varied cell types to construct complex tissue-like structures, including skeletal muscle and adipocytes, thereby advancing the development of cultivated meat.[24−26] The growing adoption of multimaterial additive manufacturing is transforming the fabrication of electronic components by leveraging advancements in materials science to develop printable inks compatible with diverse printing techniques. This capability enables the design of complex, multimaterial electronic architectures that were previously unfeasible with conventional methods. However, critical challenges persist, including print resolution, material compatibility, thermal expansion mismatches, surface wettability, and postprocessing requirements, all of which influence device performance. Despite these constraints, successful demonstrations of fundamental and advanced electronic components, such as resistors, capacitors, inductors, transistors, and solar cells, underscore the potential of 3D printing to redefine electronic manufacturing. A key obstacle remains the identification of materials suitable for multilayered, multimaterial (MLMM) fabrication, necessitating improvements in print consistency and throughput. Addressing these challenges through continued research and development will be essential for enhancing the reliability and efficiency of 3D-printed electronics.[27]

After ample analyzing Scopus data on Multinozzle in AM, which describe progressive research in the field, a total of 137 documents on multi nozzle and 1827 documents were found; however, none of the articles provided sufficient information on the topic. This review paper comprehensively assesses various extrusion and jetting printing methods using a multinozzle system. This review study focuses on the impact of various factors on printing and the nozzle system. Mathematical explanations are provided to emphasize these different aspects. The importance of the multinozzle system

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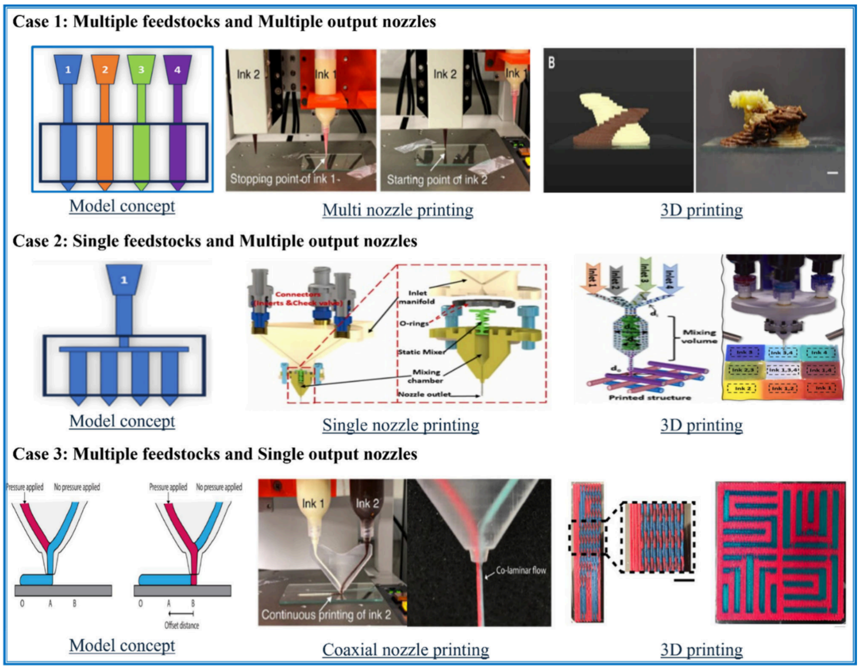

Figure 2. Conceptual phenomena for numerous approaches on multimaterials printing concept including 3 cases, their printing nozzles, and 3D printed components. Partially reused from refs 24 and 25 with permission. Copyright 2024 and 2022, Elsevier.

and the challenges it poses are also discussed. All of these elements contribute to a new perspective on the topic.

2. ADDITIVE MANUFACTURING USING MULTINOZZLE

When you want to use different colors and materials simultaneously for a specific project, there are two main challenges to overcome: the limits of the Printer's nozzle and the slow printing speed. However, the best solution to address these issues is to use multinozzle printers. In a multinozzle design, each material has its separate nozzle, allowing greater flexibility and efficiency. To prevent any inactive nozzle from interfering with the printed object, all the nozzles need to be scaled to the same height as the printed area. You can overcome the limitations and achieve better results using multinozzle printers. With such a design, the amount of trash produced during printing is greatly reduced.[30−34] A multinozzle printhead is a device that allows for the simultaneous extrusion of multiple materials through several nozzles arranged in a specific pattern. By adjusting the phase angle during printing, these printers can rapidly produce various products while adding texture to the final output.[32,35−37] Figure 2 effectively compares three different multimaterial printing strategies, each with advantages. Multinozzle printing allows for independent material control, single-nozzle printing facilitates in-line material mixing, and coaxial nozzle printing enables gradient and layered material deposition. These approaches can be strategically chosen based on application needs, such as biofabrication, electronics, or advanced composite manufacturing. Figure 2 compares three multimaterial 3D printing strategies: multinozzle, single-nozzle, and coaxial nozzle printing. In multinozzle printing, independent ink reservoirs feed separate nozzles, enabling sequential extrusion with distinct stopping and starting points, resulting in high-resolution multimaterial structures. Single-nozzle printing employs a single reservoir feeding multiple nozzles, where inks are blended in an integrated mixing chamber before extrusion, allowing tunable material composition and beneficial for mass production and fast printing. Coaxial nozzle printing utilizes a nozzle where two inks flow concentrically, forming layered or gradient structures with colaminar flow, enabling precise control over material deposition and intricate geometries.

Multinozzle technology has the potential to bring about significant implications for the advancement of architected materials. These materials exhibit exotic characteristics that arise from their engineered, periodic substructures rather than their chemistry.[38−40] Some materials are powerful yet light; changing internal structures can alter their properties. Most architectural materials are made from a single nonarchitected compound.[7,41] By altering the intended object's composition at the microscopic level, a new playing field is opened where more inventive performance qualities can be arranged into the same substance.

3. ADVANCEMENT OF MULTINOZZLE PRINTING

Managing the spatial distribution of ingredients in 3D printing facilitates the control of physical or mechanical characteristics of the produced part, opening up new possibilities that were restricted with solitary-material 3DP or conventional AM technologies.[42−44] The advent of MMAM and increased interest in the traditional use of a single material in AM technology were both prompted by the strong demand for more intricate and precise 3D architectures, which led to the fine-dimensional printing of complicated 3D geometries. Combining numerous materials, known as multimaterials, can quickly fabricate an object with properties of optical, mechanical, chemical, electrical, and capabilities.[23] Complex geometries can be additively manufactured (AM) using multiple materials to add utility, adapt to the environment, and augment mechanical characteristics. Various materials can be fabricated using extrusion-based 3D technology, but the

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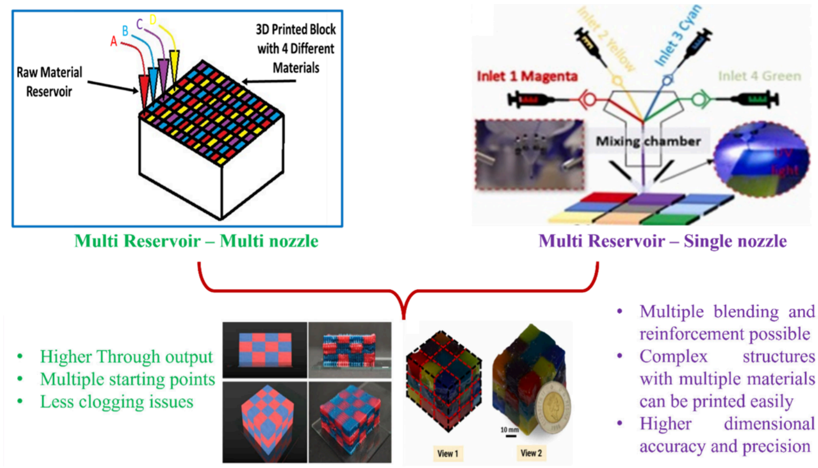

Figure 3. Gradient-colored model was printed along two different 3D printheads: multiple materials nozzles and four different inlet mixers printing heads. Partially reused from ref 25 with permission. Copyright 2022, Elsevier.

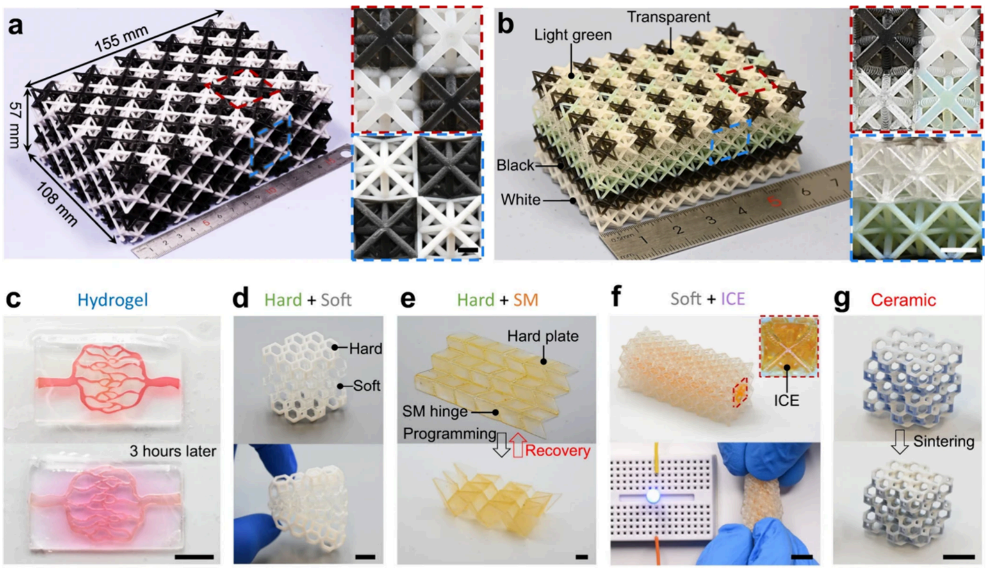

Figure 4. (a) A large-volume octet truss fabricated with two materials (scale bar: 10 mm). (b) A four-material octet truss (scale bar: 5 mm). (c) A hydrogel-based blood vessel system with two distinct colors. (d) A Kelvin foam featuring alternating hard and soft layers. (e) A Miura-origami sheet comprising rigid polymer panels and shape-memory polymer hinges. (f) A flexible IC octet truss with an ionic conductive elastomer (ICE) core surrounded by a nonconductive soft polymer. (g) A Kelvin foam constructed from two ceramic materials. Reused from ref 51 with permission. Copyright 2022, Nature Portfolio.

procedure is tedious. For instance, developing a 3D object with a volume of about one liter would require about 10 days at a resolution equal to human hair and a print pace of ten centimeters per second using a single nozzle, single material printhead. A printhead with 16 simultaneous printing nozzles would be necessary to construct the same item in less than a day.[45−48] The illustration in Figure 3 demonstrates two multimaterial 3D printing approaches: Multi Reservoir − Multi Nozzle and Multi Reservoir − Single Nozzle. The multinozzle method utilizes separate nozzles for each material, enabling higher throughput, multiple starting points, and reduced clogging, making it efficient for structured patterns, as shown in the checkerboard-printed blocks. In contrast, the single-nozzle approach blends materials within a mixing chamber before extrusion, allowing for enhanced material reinforcement, complex multimaterial structures, and superior dimensional accuracy. While the multinozzle system prioritizes speed and parallel deposition, the single-nozzle system offers greater control over material composition and precision, as demonstrated in the printed multimaterial cubes. The appropriate nozzle diameter is required to obtain a regular flow of material and a minimal pressure loss across the heating block. While designing a nozzle, the material's mechanical properties are to be considered, which are affected by the temperature of the nozzle[49,50]

Jianxiang Cheng et al. introduced a DLP-based centrifugal multimaterial (CM) 3D printing method, enabling the fabrication of large-volume, heterogeneous 3D structures with spatially controlled material distribution to achieve diverse properties and functionalities. This CM 3D printing system can construct a large-scale octet truss structure (155 × 108 × 57 mm) with alternating white and black units (Figure 4a). High-resolution zoomed-in images confirm that the multimaterial switching process maintains near-zero material

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contamination, ensuring sharp transitions between different materials. Beyond two-material printing, the CM system can integrate multiple materials within a single structure. Figure 4b showcases an octet truss comprising four distinct colors—white, black, light green, and transparent—where layers are precisely stacked, and color transitions exhibit no visible contamination. The CM 3D printing system is compatible with a broad range of materials, each offering unique properties and applications. Figure 4c presents a vascular network printed within a transparent hydrogel matrix, where red "blood" gradually diffuses over time. Moreover, Figure 4d illustrates a Kelvin foam structure featuring a soft polymer core sandwiched between intricate polymer layers. Whereas Figure 4e demonstrates a Miura-origami sheet, in which rigid polymer panels are interconnected via shape-memory polymer hinges, enabling the programmed transformation from a flat sheet to a 3D structure. Figure 4f depicts a flexible ionic conductive (IC) octet truss, composed of an IC elastomer (ICE) core encased within a nonconductive soft polymer framework, offering potential applications in stretchable electronics. Additionally, the CM 3D printing system extends to ceramic fabrication. Figure 4g illustrates a two-material Kelvin foam structure, which, following the sintering process, undergoes conversion from a ceramic-polymer precursor to a pure ceramic structure with a Young's modulus of 122.37 GPa.[51]

Figure 5a presents the schematic of the large-area centrifugal multimaterial (CM) 3D printing system, which employs a

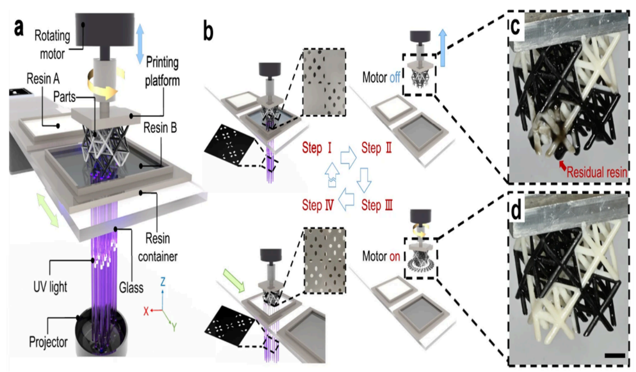

Figure 5. Digital light processing (DLP): (a) Schematic of the centrifugal multimaterial 3D printing system, (b) sequential steps for multimaterial 3D printing, (c) residual resin adhering to the printed structure upon exiting the black resin, and (d) removal of residual resin via centrifugal force. Scale bars in (c, d): 10 mm. Reused from ref 51 with permission. Copyright 2022, Nature Portfolio.

bottom-up projection approach. In this setup, a digital UV projector positioned beneath the vertically moving printing platform irradiates UV light to define each layer's thickness. A horizontally movable glass plate between the platform and the projector supports multiple polymer resin containers and selectively delivers the required resin for each slice. Notably, a rotating motor is integrated into the system to spin the printing platform, facilitating the removal of residual resin adhering to the printed structure during multimaterial transitions. Figure 5b outlines the stepwise process for fabricating a two-material octet truss. Step I prints a black material layer, followed by the platform's vertical displacement from the black resin container (Step II). Figure 5c clearly shows residual black resin adhering to the printed structure. To eliminate this, the rotating motor activates Step III, spinning the platform and leveraging centrifugal force for resin removal. As shown in Figure 5d, this process effectively removes the residual resin, ensuring clean material transitions.[23] The DLP-based centrifugal multimaterial 3D printing method is an innovative approach that can be used to create large-volume heterogeneous 3D objects. This method allows for the composition, properties, and function of a 3D object to be easily programmed at the voxel scale, making it a highly flexible and customizable solution for various applications.[23] Using centrifugal force, CM 3D printers can print heterogeneous 3D structures in wide areas using various materials, including hydrogel, functional polymers, and ceramics. Multimaterial switching becomes noncontact and highly efficient with the help of centrifugal force.[23]

Intriguingly, many materials can be used to create components since it opens up the possibility of designing multifunctional products with various features and functionally graduated qualities and incorporating responsive and functional materials.[52] Figure 6 illustrates the rotational multimaterial 3D printing (RM-3DP) approach, integrating two key advancements: (1) a multimaterial nozzle capable of generating azimuthally heterogeneous subvoxel features and (2) a printhead architecture that accommodates multiple pressure-controlled ink reservoirs while enabling unrestricted nozzle rotation. The nozzle adopts a 'shell—fan—core' configuration, wherein the fan elements facilitate the formation of an azimuthally heterogeneous microstructure. The rotational freedom of the pressure-regulated ink reservoirs and the nozzle is achieved through a four-channel rotary union, which efficiently transmits pressurized air from stationary inlets to corresponding rotating outlets, ensuring seamless material deposition.[53] A 3D printing platform has been developed to precisely control filament orientation within a given cylindrical volume. This is achieved by rotating a multimaterial nozzle at a controlled angular-to-translational velocity ratio. The resulting helical filaments have programmable helix angles, layer thicknesses, and interfacial areas between several materials. This platform enables subvoxel control and can create azimuthally heterogeneous architected filaments. Functional artificial muscles can now be fabricated using an integrated method involving helical dielectric elastomers embedded with high fidelity and conductivity within the dielectric elastomer matrix. This platform paves the way for creating multifunctional architected materials with bioinspired motifs.[53]

A new prototyping, manufacturing, and design paradigm may be developed by increasing the multimaterial processing capacity of additive manufacturing methods and the AM material catalog.[54] An integrated machine vision system is the core tenet of this new emerging technology, which enables emerging print corrections by autocalibrating printheads, 3D scanning, and closed-loop feedback and can also make products made of multiple materials.[55] Although choosing a relevant multimaterial nozzle technology is a considerable difficulty, choosing the perfect nozzle requires sufficient knowledge of the software capabilities, control parameters, and electronic pieces of machinery available in the 3DP equipment to produce numerous material products.

A multinozzle extruder allows simultaneous printing of five distinct materials and colors. According to the research by Abilgaziyev et al., multimaterials functional components can be fabricated using switching of the extruder rather than stopping the operation.[56−59] Extruders of the Bowden type are chosen to isolate the driving components from the heated ending.

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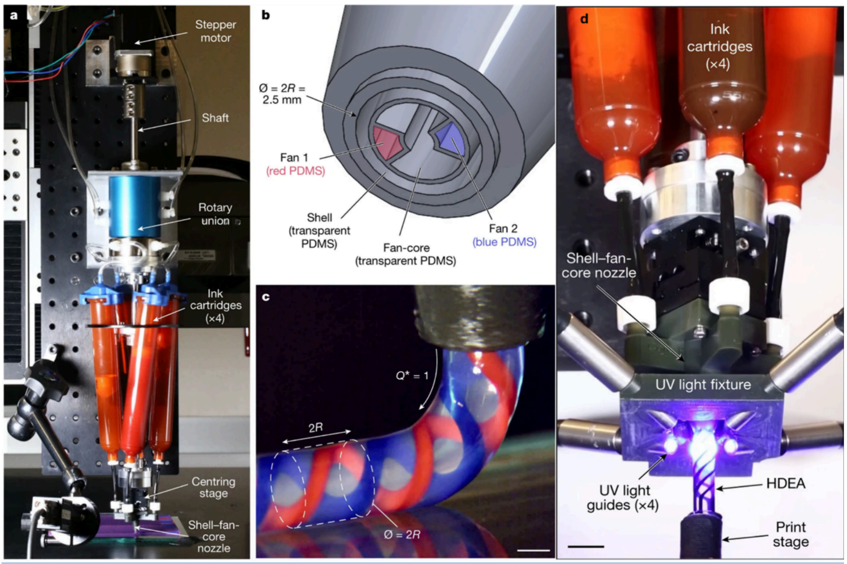

Figure 6. Rotational multimaterial printing with modified nozzle designs up to sub voxel control. Adapted from ref 53 with permission. Copyright 2023, Springer Nature Group.

Additionally, the extruder is only powered by two stepper motors, significantly reducing the hot-ends weight and bulk and speeding up production. According to computational Finite Element Analysis (FEA), Acrylonitrile butadiene styrene (ABS) has the potential to be used as a structural substance owing to its affordable production cost, enhanced strength, and lightweight; ABS can be used as a structural substance, according to computational finite element analysis.[60,61] Some researchers developed antennas using a multimaterial additive manufacturing printer (3Dn-300) based on FDM that was put forward for trade by Scrypt Inc. Pa et al. designed a low-profile antenna with a ground plane made of artificial magnetic conducting. This system incorporates two deposition heads, one of which distributes Polycarbonate (PC) utilizing the fused deposition method to layered several dielectric apparatuses, and the other utilizes a microdispensing technology to print silver conductive elements[62−64] Khondoker et al. studied the Functionally graded materials (FGMs) composed of nonmiscible thermoplastics that can be manufactured using a dual extruder customized for fused filament fabrication (FFF) for AM of various materials. The suggested dual extruder can print two mixed and static polymers among a single nozzle to increase the adherence of the materials fed into it. The dual-extruder was distinguished by its ability to print components out of high-impact polystyrene (PS), polylactic acid (PLA) and acrylonitrile-butadiene-styrene (ABS). The automatically linked extrudates also greatly decrease failure due to adhesion inside and concerning strands.[65,66]

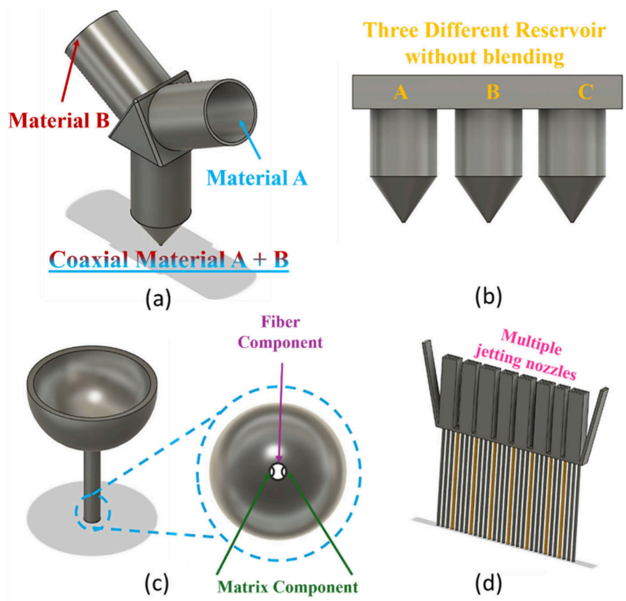

Figure 7. (a) Two material nozzle extruders with coaxial printing, (b) three material nozzle extruders, (c) extruder nozzle for two matrix and fibers between it, and (d) multimaterial nozzle extruder.

Figure 7 illustrates the nozzle extruder design concerning the number of materials used: (a) nozzle with two different materials, (b) the design of the nozzle contains three materials, (c) this design is mainly used for fiber-reinforced polymer composite materials in which the matrix comes from the center, and fibers are fed from the side provision, and (d) this design is made for using multiple materials such as binder jet printing. The implementation of multi material printing can be extended for the 4D printing technique as the integration of 4D printing with mechanical metamaterials has unlocked unprecedented possibilities for multifunctional, stimuli-responsive architectures with transformative applications in biomedical devices, soft robotics, and energy storage systems. This review highlights the interdisciplinary nature of the field, bridging mechanics, materials science, and biology to drive innovation. Despite theoretical advancements, practical deployment remains constrained by challenges such as suboptimal mechanical properties, limited control over deformations, and the necessity for extensive validation in biomedical contexts. The adoption of machine learning and artificial intelligence is poised to optimize design and manufacturing, enhancing print quality, cost efficiency, and material performance. Future research should prioritize dynamic bonding mechanisms and multistimuli-responsive materials to enable self-healing and reprogrammable functionalities. Addressing the complexities of shape morphing under diverse stimuli, ensuring long-term durability, and developing cost-effective fabrication strategies will be crucial for translating 4D-printed metamaterials into scalable, real-world applications.[67] The field of mechanical metamaterials has witnessed significant advancements with the advent of 3D and 4D printing technologies, enabling the fabrication of complex microstructures with tailored mechanical properties. While 3D printing has revolutionized the design space, the integration of 4D printing introduces intelligent tunability, expanding the functional adaptability of these materials. However, challenges persist, particularly in the precision and scalability of micro- and nanoscale architectures, the limited range of printable materials, and the underexplored potential of multimaterial and composite printing. Additionally, postprocessing techniques remain critical to mitigating residual stresses and enhancing mechanical performance. The multifunctionality of mechanical metamaterials is a key frontier, necessitating innovative design strategies to achieve integrated properties such as vibration isolation and thermal protection. Addressing these challenges requires a concerted interdisciplinary effort, merging expertise in mechanics, materials science, and electronics to develop next-generation metamaterials with transformative engineering applications.[68,69]

3.1. Extrusion-Based Printing. Most widely used techniques, including fused filament fabrication (FFF), rely on material extrusion and direct ink writing (DIW). Extrusion in additive manufacturing systems usually constructs multicolor and multimaterial objects using multiple nozzles mounted one after the other on the same carriage. By accelerating the processing speed through continuous operation, numerous nozzles can make it easier to produce several printings components; Table 1. provides a summary of the multinozzle AM method. Since multinozzle printheads often drop filaments based on the configuration of the nozzle array, their use is limited to the production of repetitive patterns.[74]

The illustration in Figure 8 demonstrates how a 64-nozzle extruder was used to print the two layers of the 3D product, increasing production efficiency and reducing production time. Skylar-Scott et al. utilized a multimaterial multinozzle printing head to produce a recurring voxelated prism of $40 \times 40 \times 10$ mm^3 produced using an organic ink; the same material was used in four distinct color schemes utilizing the multimaterial multinozzle system print at a reasonable tempo of 40 mm/s.[75] The outcome of 3D printing is affected by any aspect change of the nozzle design, more than the deposition rate and road breadth; the layer thickness influences the surface roughness. The nozzle, geometrical errors, the material's fluctuating temperatures, pressure changes, and printing time influence the surface finish. The nozzle's texture and surface finish have impacted since it came into touch with the printed material last[44,76]

In the illustration shown in Figure 9, the reciprocating screw used to transport the material from the multinozzle die is an example of an additive manufacturing process based on extrusion. FFF is an innovative manufacturing technique that can create multimaterial components and is useful in mechanical and civil engineering domains, notably in structural applications.[77] A set of stepper motors work together to control the motion of the nozzle, which the desired component's CAD model directs. FFF printing technique commonly used materials made of thermoplastic polymers like polylactic acid (PLA), polyphenyl sulfone (PPSF), Nylon, polycarbonate (PC), PC-ISO, acrylonitrile butadiene styrene

Table 1. Comprehensive Analysis of Multimaterial Printing Using Single and Multinozzle Systems

Multimaterial with multinozzle	Ref	Multimaterial with single nozzle	Ref
The mechanism comprises a series of nozzles or combined two or more nozzles.	70	The mechanism involves the extrusion of multiple materials from a single nozzle.	57
Simultaneous printing of multiple materials based on nozzles or heads.	56	A single nozzle can print 3 to 4 materials at a point because involving more than 4 outputs in a single nozzle will be challenging to handle.	60
Multiple mechanisms can be active, such as linear, rotary, or changing head.	71	The mechanism can be coaxial, cross head, or T-junction.	31
It mainly consists of 2 parts: filament-driving cold-end and hot-end.	1	To produce functionally graded materials using many additive materials, including immiscible thermoplastics	72
The triextruder head consists of four major components: a nozzle, a split melt chamber, and two guideways.	8	The single nozzle extruder system's cold end consists of the toothed gear's rotation against a bearing by a stepper motor.	9
Two inlet angles: 45° from horizontal The melt chamber has a third inlet with 90° from horizontal		Multiple materials are fed into the heated barrel. The barrel rotates and mixes the materials, and the mixed materials fall on the bed, which has movement in the *z*-axis.	
This method involves scanning the region of interest with a line profilometer to collect data points, extrapolating substrate topography from the point cloud, computing individual print paths for each nozzle in the printhead array, and guiding the printhead to pattern ink filaments over complex topographies.	13	Zhang et al. developed a method for 3D printing fiber-reinforced smart patterns for electronic textiles in a single step, using silver palladium paste, ethanol as a conductive material, and Glass Bend Flexi as a flexible substrate, with coextrusion of inks via an Anycubic 13 MEGA 3D printer equipped with a coaxial spinneret.	17
This multinozzle, multimaterial 3D printing technology, based on Direct Ink Writing, uses SLA and specialized nozzle arrays to intricately combine high-density soft matter with various ingredients at the voxel level.	23	Piezoelectric sensors with silver electrodes coextruded in a single step using DIW and a robotic 3D printer demonstrated effective strain sensitivity, with a linear correlation between generated voltage and applied strain.	34
Material jetting (MJ) is an additive manufacturing process that uses drop-on-demand or continuous material deposition, allowing for the printing of multiple materials, including support, with alternating nozzles in systems like PolyJet.	37	A Prusa 8 in. i3v kit with a Rambo 1.3v motherboard was used to set up dual stepper motors for extruding two materials, with a custom-built dispensing apparatus for melted sugar using a gear-driven piston system inspired by the "Baricuda Extruder".	40
A DIW-based method was used to print silicone in two colors, incorporating graphene-based electrodes for electrochemical energy storage and magnetorheological fluid in a silicone matrix for layered fabrication.	41	Vat photopolymerization uses liquid photopolymer resin and light sources to print parts layer by layer, supporting multimaterial printing with challenges in contamination control, but offering advantages in dimensional accuracy, surface finish, and material variety.	73

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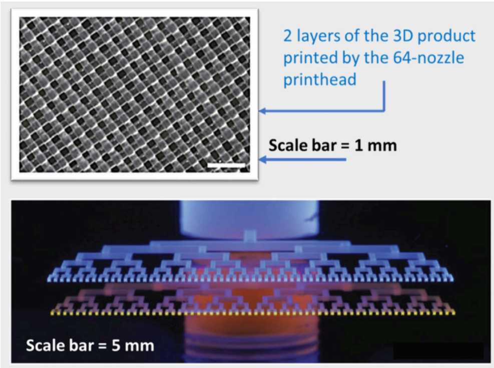

Figure 8. Optical representation of a two-layer lattice printed using a 64-nozzle printer with 200 μm by 200 μm nozzles spaced 400 μm apart (scale bar: 1 mm). Reused from ref 74 with permission from. Copyright 2013, John Wiley & Sons.

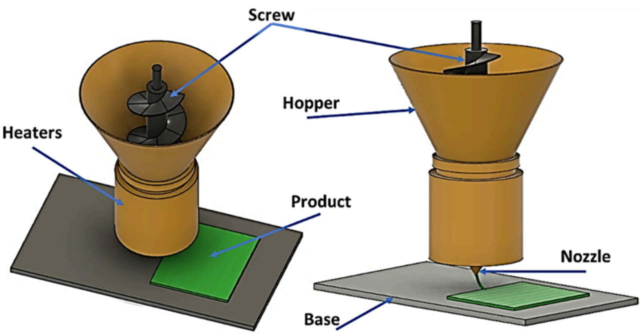

Figure 9. Extrusion-based printer of additive manufacturing.

(ABS), PC-ABS composites and biodegradable polymers. The material is softened or melted in FFF by heating the extrusion nozzle, and the degree of heat of the nozzle is determined by the substance that can be carried out. For instance, the opening temperature for ABS and PLA is typically maintained at 240–250 °C and 190–200 °C, respectively. Since the build platform's temperature (roughly 70 °C for PLA) is lower than the nozzle's, after cooling, the extruded material assumes the required shape following solidification. After the initial layer of polymer material has been deposited, the build surface moves vertically with a height equivalent to the layer's thickness.[78] Three-dimensionally printed poly(lactic acid) (PLA) and poly(ε-caprolactone) (PCL)-based biopolymers have emerged as promising candidates for biomimetic scaffold fabrication, offering a versatile platform for tissue engineering applications spanning bone, cartilage, skin, nerve, cardiac, tendon, dental, and vascular regeneration. The integration of bio ceramics and bioactive glasses (BGs) into these polymeric matrices enhances their bioactivity, mechanical performance, and degradation kinetics, effectively addressing limitations such as stress concentration and inflammatory responses commonly associated with metallic implants. Notably, the development of 3D-printed biodegradable PLA-based stents has demonstrated remarkable hemocompatibility and anticoagulant properties, providing a viable strategy to mitigate thrombosis and restenosis risks in cardiovascular interventions.[79] The study by Vincent S. D. Voet et al. provides a critical assessment of advancements in sustainable photopolymers for 3D printing, underscoring the imperative to develop environmentally benign alternatives. Vat photopolymerization is identified as a versatile technique for fabricating intricate geometries, facilitating the evolution of additive manufacturing technologies. The transition toward biobased photopolymers, derived from renewable feedstocks such as vegetable oils, terpenes, starch, and lignin, signifies a departure from conventional fossil-based acrylates and epoxides. However, challenges persist in attaining optimal mechanical performance and structural integrity. The integration of biobased nanofillers, including cellulose nanocrystals and chitin nano whiskers, has demonstrated potential in enhancing the material properties of these resins. Despite the development of biodegradable formulations, comprehensive studies on degradation pathways and recyclability remain limited. The emergence of covalent adaptable networks, particularly vitrimers, offers a promising route for enabling reprocess ability and repairability in thermosetting photopolymers, marking a pivotal advancement toward sustainable additive manufacturing.[80] Direct and Bowden extruders are the two extruder kinds most frequently used today. The majority of FFF 3D printers are of the straight extruder variety. A motor, heater, and nozzle that draws filament directly from the freezing end and feeds it into the heated ending are the moving parts of this type of extruder.[39] Multinozzle, the hot-end extruder system offers various applications and an emerging research scope.[81]

A distinct 3D printing method called direct ink writing allows for patterning high-performance materials. However, current iterations rely on the layer-by-layer extrusion of cylinder-shaped filaments through a single nozzle constructed of a single material. When using the DIW method for multimaterial 3D printing, which offers a larger variety of materials, various extrusion nozzle designs, such as those shown in Figure 10, can mix several formulations into complex

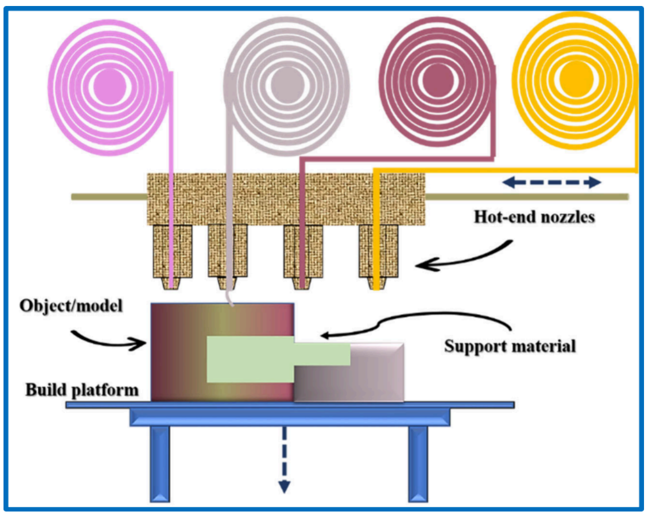

Figure 10. Schematic representation of 3D printing

structures. Utilizing several nozzles enables advantages, including the use of nozzles of different diameters. Due to the availability of various sizes, clogged nozzles can be replaced; model printing will take less time and have intricate details. The same part's mechanical, resolution, and functional characteristics can be improved with these advantages. For example, adding carbon fiber reinforcement to composite materials increases strength and modulus. However, it also results in more brittle composites than their single-material counterparts due to inappropriate fiber-to-polymer matrix bonding and high levels of brittleness. Additive manufacturing

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Table 2. Various Forms of 3D Printing and the Nozzle Details

Sr. No	Advanced technology	Name of the 3D Printer company	Material used	No. of nozzles	Resolution (mm)	Refs
1.	FDM	craftBot3	PLA, ABS	Two	0.1	83, 84
		Duplicator			0.1−0.3	
		Zortax			0.09-.029	
		MakerBot			0.02−0.4	
2.	DIW	Envision TEC	Paste or gel	Two	0.1	85
3.	MJ	Object 30 pro	Materials from the Vero family	Two	0.016	86

provides the remedy to this challenge as it can incorporate one more (third) material into the system. Adding a modest number of soft material phases into a 3D topology built with only a tiny decrease in the composite stiffness and flexibility may boost impact characteristics and improve the overall damping coefficient and energy absorption. An optimal DIW system can extrude a multimaterial filament with a high switching frequency to produce voxel elements along its length with specific compositions. (Multimaterial additive manufacturing or multimaterial 3D printing) MM3D printheads can deposit eight different materials, each traveling through a separate network of bifurcating channels inside the Printhead before coming together as one ink flow before the nozzle exits. Each nozzle within the Printhead must possess an inner diameter exhibiting a coefficient of variance below 5% to ensure uniform and reliable printing outcomes. Various process variants have been created for multiple material extrusion printing technologies. An elevated level of shear force is required to facilitate the extrusion process of viscous substances. Estimating materials' viscosity and shear can be derived using the Stokes−Einstein equation.[82] (eq 1):-

$$\eta = \frac{kT}{6\pi D R_s} \tag{1}$$

where R_s = radius of the particle, D = diffusion constant, η = dynamic viscosity, T = absolute temperature, and k = Boltzmann's constant.

Additionally, (multimaterial additive manufacturing or multimaterial 3D printing) MM3D printing can be utilized to make more intricate items, such as actuating robots. Zhenhua wang and team created a soft robot with embedded pneumatic channels that allow the soft muscles to be consecutively compressed with the help of a vacuum, causing it to walk. The robot is made of flexible and rigid elastomers and has a millipede-like design. With a load equal to eight times its weight, the robot had to move at a speed of about half an inch per second. It may also be working with other robots to transport greater loads. The numerous types of 3D printing technologies are displayed in Table 2. and the relevant technical details, such as the material used, the number of nozzles, and the resolution (mm).

The study presents an advanced 3D-printed gripper that integrates soft and rigid materials to enable variable stiffness control, addressing the limitations of task-specific grippers. Utilizing a multimaterial fused filament fabrication (FFF) approach, the gripper achieves a monolithic structure, reducing assembly complexity and enhancing reliability. A key innovation lies in incorporating Joule heating in conductive polylactic acid (c-PLA), allowing on-demand stiffness modulation for adaptable grip strength. Additionally, embedded sensors made from conductive thermoplastic polyurethane (c-TPU) provide real-time feedback on gripping force, enhancing object recognition and manipulation. The gripper's versatility in handling diverse objects positions it as a promising tool for automation in robotics and manufacturing. This work advances soft robotics by integrating compliance, rigidity, and sensing in a unified design, offering a pathway for future innovations in robotic grippers.[87] The study by Laszlo Jaksa introduced a novel additive manufacturing (AM) technology designed to fabricate anatomically realistic models, demonstrating the capability to print multimaterial structures essential for functional applications. The successful production of a medical image-based anatomic model underscores the technology's potential for diverse applications, including medical education, device testing, and preoperative planning, thereby enhancing clinical training and procedural preparation. However, the findings emphasize the necessity of further investigation into geometric constraints and mechanical properties to ensure accurate replication of human anatomical complexities. Additionally, the study established strong adhesion between silicone and polylactic acid (PLA), a critical factor for constructing intricate multimaterial structures. However, the adhesion also presents challenges, such as removing support structures postprinting.[88] Ivonbony Chan and team integrate innovative fashion design, ergonomics, and 3D printing technology, demonstrating their synergy in creating a unique fashion prototype. This interdisciplinary approach is pivotal for advancing fashion design methodologies. The research offers theoretical and practical contributions, mainly through developing a structured design process model that aids designers, researchers, and engineers address design challenges. The model underscores the necessity of bridging traditional design expertise with computational proficiency, a persistent challenge in fashion. Furthermore, the study highlights the application of 3D body scanning technology, which enables the creation of precise garment meshes that enhance fit and comfort by incorporating ergonomic considerations. However, limitations in current 3D printing technology, including color fidelity, platform size, and material costs, restrict large-scale adoption in fashion. Addressing these challenges, the study advocates further research into 3D color printing to refine existing capabilities and facilitate the integration of 3D printing into mainstream fashion and textile industries. The findings underscore the transformative potential of color printing in design innovation, emphasizing the necessity for the fashion industry to adapt to advancements in additive manufacturing to maintain competitiveness. Overall, this research enhances understanding 3D printing applications in fashion and establishes a foundation for future innovations in this rapidly evolving field.[89]

3.2. Binder Jetting Printing. Binder Jetting (BTJ) is a process to create sand molds for casting ceramic and metal components. The process involves spreading a thin layer of particles using rollers and then selectively jetting a liquid ink binder onto the particles using an inkjet nozzle. This binds the particles together and creates the desired shape of the

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component based on the 3D CAD model of the required component. Use a heater based on lamps, and the binder is then evaporated, causing the release of the back-stacked particles. Heaters can be used in systems for curing and moisture control, but not compulsorily. Following the first layer's completion, the building platform is lowered by a space equivalent to the elevation of the layered slices until the three-dimensional part is fabricated and the procedure is replicated. Hence, a retrieved body called a green body is immersed in untainted powder, and to enhance its mechanical qualities and create a finished product that can be used, it requires a series of postprocessing procedures.[90]

The additive manufacturing jetting technology for four different materials simultaneously is shown in Figure 11. The

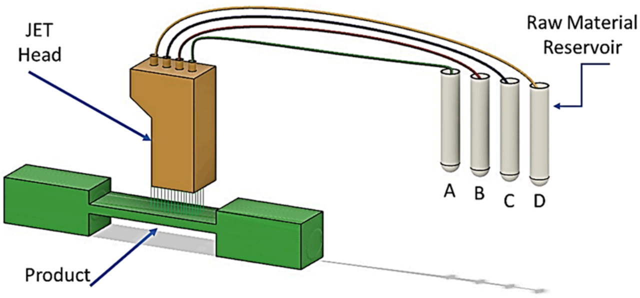

Figure 11. Jetting-based printer of additive manufacturing.

single-nozzle inkjet method presents several inherent challenges, such as functional ink overheating, reduced resolution, head obstruction, and increased time consumption. The multinozzle inkjet approach overcomes these difficulties and achieves high resolution throughout the process. Arshad Khan et al. evaluated the electrohydrodynamic (EHD) inkjet with five nozzles with integrated counter electrodes. The multinozzle printing head comprises copper electrodes, copper ring extractors, and glass nozzles; all of these are comprehended into a simple structure. The multinozzle EHD inkjet process was validated with several prototype electronic circuits made of various high-resolution substrate materials.[91]

The nozzle diameter, pressure, and temperature are important nozzle design parameters; a representative diagram of the nozzle tip is shown in Figure 12. The ideal nozzle size and diameter regulate the crucial factors of the feeding syringe and the heating blocks; some factors affecting the multinozzle

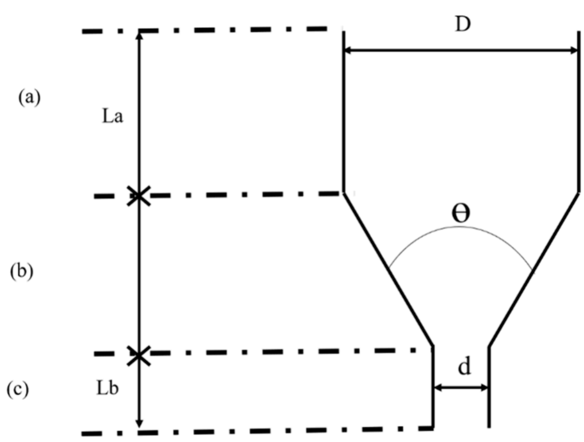

Figure 12. Pictorial representation of the tip of the nozzle.

AM are represented in Table 3. The drop in pressure across the heating block is the primary change observed when altering the nozzle's diameter. The pressure decrease is calculated at every location along the nozzle, and its geometry is estimated using the following equations (eqs 2−5).[92]

$$\Delta P = \Delta P_A + P_B + P_C \tag{2}$$

$$\Delta P_A = 2L_\alpha(\vartheta/\varnothing)^{1/m}\left(\frac{m+3}{\left(\frac{D}{2}\right)^{m+1}}\right)\exp[\alpha(1/T - 1/T\_\alpha)] \tag{3}$$

$$\Delta P_B = \left(\frac{2m}{3\tan\left(\frac{\theta}{2}\right)}\right)\left(\frac{1}{d^{3/m}} - \frac{1}{D^{3/m}}\right)\left(\frac{D^2}{2(m+3)2^{m+3}}\right)^{1/m} \exp[\alpha(1/T - 1/T\_\alpha)] \tag{4}$$

$$\Delta P_C = 2L_b(\vartheta/\varnothing)^{1/m}\left(\frac{(m+3)\left(\frac{D_1}{2}\right)}{\left(\frac{D}{2}\right)^{m+1}}\right)\frac{1}{m} \exp[\alpha(1/T - 1/T\_\alpha)] \tag{5}$$

where ΔP = total pressure drop, T = absolute temperature, θ = nozzle angle, and m and $\varnothing$ = power-law fit parameters.

4. CHALLENGES AND FUTURE OUTLOOK

MMAM has made remarkable strides in recent years. However, several issues still need to be resolved, such as surface finish, poor scalability, low production throughput, a lack of material variety, weak interfacial bonding between various materials, and high cross-contamination. Multimaterial additive manufacturing (MM-AM) holds immense potential for fabricating complex, high-performance structures with tailored functionalities. However, several critical challenges must be addressed to fully exploit its capabilities, particularly in material compatibility, defect mitigation, and process optimization.[17,66,96−99]

Key Challenges in Multi-Material Additive Manufacturing.

- **Material Compatibility**: Integrating dissimilar materials often leads to issues such as interfacial instability, phase segregation, and intermetallic compound formation, which can compromise mechanical integrity and functionality. Understanding material interactions at the microscale and nanoscale is crucial to overcoming these limitations.
- **Defect Formation**: High stress concentrations, thermal gradients, and differences in material properties lead to defects such as delamination, porosity, and microcracking, particularly at material interfaces. Advanced in situ monitoring techniques and real-time feedback control are required to minimize such defects.
- **Process Optimization**: The variability in thermal expansion coefficients, curing kinetics, and rheological properties of multimaterial systems demands extensive optimization of processing parameters. Integrating adaptive control algorithms and machine learning-driven optimization can significantly enhance printing reliability and repeatability.

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Table 3. Multinozzle Additive Manufacturing Techniques with Their Affecting Parameters

Sr. No	Techniques	Material used	Nozzle type	Nozzle diameter (mm)	Nozzle temperature (°C)	Melt Viscosity (pa s)	Printing speed (mm/s)	Ref
1.	FDM	PEEK	Dual	0.4	210–250	350	40	93
2.	DIW	Hydrogel	Dual	0.4	NA	10^{-1}–10^{3}	500	94
3.	BJ	Liquid binder	Dual	0.025	50	0.12	>400	95

Future Research Directions. While significant progress has been made in MM-AM, further research is imperative to overcome existing challenges and push the boundaries of multimaterial fabrication. By integrating advanced material science, computational modeling, and intelligent process control, MM-AM can be positioned as a transformative technology across diverse industrial applications, including aerospace, biomedical engineering, and advanced electronics.[100−102]

- **Gradient Interfaces**: Developing compositionally graded transition zones can mitigate residual stresses and improve interfacial bonding, thereby enhancing structural performance. Functionally graded materials (FGMs) offer a promising avenue for creating seamless interfaces in multimaterial systems.
- **Machine Learning Applications**: Leveraging artificial intelligence for process parameter optimization can refine deposition strategies, reduce defects, and accelerate the development of novel multimaterial architectures. AI-driven models can predict optimal printing conditions and adapt dynamically to real-time variations.
- **Nanoscale Fabrication**: Advancements in nanoscale 3D printing techniques, including multiphoton lithography and electrohydrodynamic jet printing, can enable the fabrication of high-resolution, multimaterial structures with unprecedented precision. Such capabilities could revolutionize applications in microelectronics, biomedical implants, and soft robotics.
- **Multi-Functional Material Systems**: The integration of conductive, dielectric, and bioactive materials within a single construct can unlock new opportunities in next-generation electronics, energy storage devices, and biomedical scaffolds. Innovations in charge-programmed printing and voxel-based material deposition can drive advancements in these domains.
- **Expanding Dimensionality in AM**: The emergence of 4D, 5D, and 6D printing methodologies, incorporating dynamic and responsive material properties, presents exciting prospects for adaptive and intelligent structures. Multinozzle and direct ink writing (DIW) systems with customized deposition patterns can further enhance material adaptability and functional diversity.

5. CONCLUSION

Scientific advancements and technological progress are poised to experience a significant acceleration across numerous domains due to the continued evolution and innovative utilization of multimaterial additive manufacturing (MMAM). MMAM's pioneering application in novel fields is expected to revolutionize various industries. The utilization of multinozzle 3D printing technology offers substantial advantages, including reduced wastage, diminished labor expenses, and heightened efficiency in crafting multicolored, customizable products. This technology not only minimizes waste but also optimizes labor costs, thereby significantly enhancing production efficiency. Its potential for integrated deployment across energy, electronics, and material sectors expands the scope of 3D printing designs beyond intricate geometries, allowing for more diverse and intricate product designs. The efficacy of 3D printing outcomes is intricately tied to nozzle design, where the integration of process planning and appropriate nozzle features profoundly influences both developmental timelines and costs. The strategic amalgamation of process planning methodologies with meticulous nozzle design features holds the key to minimizing developmental expenses and expediting production timelines. By expediting the production of additively manufactured parts, multinozzle additive manufacturing presents an opportunity to reduce costs while optimizing workflow efficiency. Multinozzle additive manufacturing represents a promising approach in creating materials suitable for broader and more efficient use in manufacturing applications. This approach exhibits potential as a robust alternative to single extruder systems across various industrial applications, thereby ushering in a new era of manufacturing possibilities.

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Author Contributions

Jigar Patadiya contributed to material preparation, data collection, and article writing. **Balasubramanian Kandasubramanian** contributed substantially to conceptualization and discussion and reviewed the manuscript before submission. **Sreenivasan Sreeram** contributed to material preparation, data collection analysis, and article writing. **Priyanka Patil** contributed to the material preparation and article writing. **Rihan Mujawar** contributed to the reviewing and writing of the article. **Amol Indalkar** contributed to the reviewing and writing of the article. **Mohamed Kchaoue** contributed to the discussion, reviewing manuscript before submission. **Faisal Khaled aldawoode** contributed to the reviewing and writing of the article.

Notes

The authors declare no competing financial interest.

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