Review on Additive Manufacturing and Emerging Materials: Pathways to Next-Generation Production

Murali Krishna Alla[1]; Dr. B. Naga Raju[2]

[1]Research Scholar, Department of Mechanical Engineering, AU, Visakhapatnam.
[2] Professor, Department of Mechanical Engineering, ANITS, Visakhapatnam.

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Abstract: Additive Manufacturing has transformed standard manufacturing practices by allowing the stepwise making of sophisticated geometries using multiple material types. This study provides a detailed analysis of the evolutionary trends, design taxonomy, and performance improvement of materials implemented in AM, pertaining to their intrinsic characteristics, operational procedures, and industrial significance. The major materials currently used contain polymers, ceramics, glass, and metals, each adding a unique mechanical, thermal, and chemical strength and limitation. Modern developments include the development of biocompatible photopolymers, eco-friendly thermoplastics, advanced metal alloys, and high-performance ceramics specialized for aerospace, medical, and engineering uses. Innovative domains in AM materials Contain graphene-reinforced composites, shape-memory polymers, conductive nanocomposites, cellulose-derived biopolymers, and 4D bio-inks capable of adjusting to environmental conditions. These progressions represent a change from basic prototyping for the attainment of multifunctional, high-performance, and eco-friendly manufacturing systems. The review marks the material advances in AM. Initially developed in the 1980s to its existing stage of technological sophistication, signaling landmark achievements and industrial implementation. Sustained progress in material science continues to be central to setting the stage for the next era of AM, providing enhanced performance, enhanced resource efficiency, and remarkable design applicability across sectors, including industries such as aerospace, healthcare, and manufacturing.

Keywords: *Additive Manufacturing, 3D Printing Materials, Polymers, Metals, Advanced Composites.*

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I. INTRODUCTION

AM, commonly referred to as Direct Digital Manufacturing, signifies a transformative milestone in manufacturing, accelerated by the swift evolution of information and communication technologies[1]. Using 3D printing, a design developed in one area of the world can be developed in another, providing chances that challenge and reshape conventional production techniques [2]. Recent manufacturing methods highlight the usage of highly advanced, smart, and revolutionary materials, along with the traditional options like plastics, ceramics, metals, and composites, to cater to a diverse array of performance requirements. Within this condition, detecting the suitable materials for AM becomes an important consideration [3]. The process parameters and material behavior during printing is essential for developing novel materials capable of addressing future industrial challenges [4]. For Additive Manufacturing (AM) to achieve optimal efficiency, materials must not only be compatible with the chosen process but also easily formable, amenable to output techniques that enhance their properties, and capable of delivering the desired performance in service.

As AM technologies have developed, required groups of materials have become strongly connected to particular techniques and applications. The performance of AM components—whether physical, mechanical, optical, thermal, or electrical—depends strongly on their underlying microstructural characteristics [5]. In the case of metal-based AM, working with metals remains a demanding task, largely because the extreme heat involved in processing alters the microstructure. Ongoing research focuses on improving dimensional precision and enhancing mechanical strength, while also addressing the challenge that alloy properties do not always translate seamlessly across different systems [6]. Compared to conventional metals, AM is being used for unconventional materials, such as food items such as pasta, candy, and ice cream; molecularly structured nutrients developed for medical usage; and the

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bioprinting of human cells. These developments are progressively widening the range of AM and resulting in completely new fields. The wide range of accessibility of 3D printing materials has stimulated the advancement of a multibillion-dollar international marketplace. A market survey anticipated the industry's value to jump from $6.98 billion in 2017 to $12 billion in 2018, accentuating the huge requirement for materials suitable for AM technologies [7]. Even though plastics used to be the most accepted, increased importance is being focused on advanced and eco-friendly choices, like bio-based resins formed from sustainable sources like corn and soybean oil. SmarTech Markets predicted that plastic-based 3D printing would be responsible for $1.4 billion in sales in 2019. Even with significant growth, difficulties regarding materials remain evident, such as maintaining increased melting points, attaining exact control over layer thickness, handling the trade-off between printing speed and exactness, and improving the production. Dealing with these difficulties requires ongoing development in both material production and AM process engineering to provide solutions which are high-performing, resourceful, and environmentally sound.

II. POLYMERS

Thermoplastic polymers, accompanied by uncured thermosets, hydrogels, pastes, and remaining moldable substances, have been fundamental to 3D printing tech for many years [9]. In this, universally recognized thermoplastic filaments like ABS, PLA, and PVA are crucial for manufacturing a wide assortment of parts used widely in multiple industries [8]. The implementations of thermoplastics and thermoplastic rubbers in AM persist in growing as current studies focus on the essential limitation on the z-axis, which is more vulnerable compared to the x and y axes in fused filament fabrication. Studies into improved thermal welding methods attempt to develop this "z strength," a characteristic that plays a vital role in high-performance uses, such as load-bearing prosthetic devices and implantable devices [8In addition, a variety of traditional thermoplastics and thermoplastic rubbers have undergone assessment and received patent recognition for future use in additive manufacturing [9].

- *Photopolymers*

These photopolymers are thermosetting polymers that transition from liquid resins to solid structures upon exposure to light sources such as lasers, lamps, projectors, or LEDs, and once cured, they cannot be remelted. Their chemical structure commonly comprises photo-initiators, oligomers that perform the role of binders, and monomers. Upon being lighted, the photo-initiators convert light energy into chemical energy, causing reactions in which oligomers and monomers unite to establish cross-linked, 3D polymer networks. By modifying the selection of oligomers and monomers like epoxies and polyester urethanes, as well as pigments, fillers, or additives, the final material characteristics, such as viscosity and stiffness, can be meticulously adapted to conform to performance demand. Capable of fine-tuning to suit photopolymers, they are employed in fields such as jewelry model casting, dental crown customization, and advanced biomedical implants [10].

- *ABS Material*

ABS is a long-lasting thermoplastic known for its toughness and high dimensional accuracy [8]. Developed through acrylonitrile, butadiene, with styrene polymers, it is considered to be one of the prevailing materials in personal and household 3D printing. In AM, ABS sections are usually formed via fused deposition modeling (FDM) and are specifically opted for huge components due to their strong mechanical characters [11]. The material is compact, impact resistant, abrasion resistant, affordable, and obtainable in several chemical grades. Having a melting temperature of nearly 200°C, ABS develops components that are warp resistant and cracking, resulting in suitability for enclosures, casings, and functional end-use components. Its broad range of uses includes automotive components, musical instruments, Lego bricks, instant tooling solutions, and speculative prototypes [8, 12].

- *Polylactide*

Polylactide, commonly known as polylactic acid (PLA), is among the most widely used thermoplastics in 3D printing. Developed from sustainable feedstocks like cornstarch and sugarcane, PLA is eco-friendly and naturally decomposable. When heated, it exudes a mild sweet aroma, characteristic of its sugar-based origin. The material is non-harmful, warping resistant, and less complicated to manage than ABS, despite offering relatively lower mechanical strength [8]. Having a melting point of about 173°C, PLA facilitates the making of prints with fine detail and reduced error. Even with its merits, it remains sensitive to improved temperatures, which might bring about warping or deformation. PLA is also convenient to sand, drill, and cut, resulting in its suitability for quick prototyping, packaging uses, and candy wrappers, as well as bioabsorbable sutures [12, 13].

- *Nylon*

Nylon, a versatile polyamide, is regarded for its prominent strength, toughness, and flexibility and is broadly recognized as a "white, robust, and flexible" material [15]. Because of its water-absorptive behavior, it uptakes moisture from the vicinity, which can compromise print quality. To deal with this, nylon filaments are retained under dry conditions and routinely processed using vacuum systems or high temperatures [14]. Proper printing usually requires extrusion at close to 250°C, with the filament pre-dried at 160–180°F for a time of 6–8 hours. Once completely dried, nylon developed smooth and glossy prints with high interlayer adhesion. Its high resistance to abrasion and mechanical influence results in it being apt for functional prototypes, sports gear, consumer electronic components, and temporary phase manufacturing applications [8, 16].

- *Polycarbonate*

Polycarbonate (PC) is a superior-performance thermoplastic. Esteemed for its weight-saving characteristic, density, and exceptional tensile strength [8]. Even though it

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is naturally transparent, it can be highly tintable and depicts superior heat resistance contrasted to acrylic materials [17]. To enable precise printing, extrusion temperatures between 260 and 300°C are needed to attain robust interlayer bonding. Reinforced grades, like carbon fiber-filled PC, exhibit improved strength and thermal stability, resulting in them being apt for required applications like drone components, RC vehicles, intake manifold geometry, and other improved performance systems [8, 17].

➢ *Polyvinyl Material*

PVA, is frequently used in additive manufacturing to form support members for intricate designs and overhanging features [8]. After the printing procedure, PVA is water-soluble at warm temperatures within nearly 20 minutes, removing the requirement for support material that easily dissolves in warm water. Being non-toxic and customer-friendly, it operates at maximum effectiveness in dual-extruder printers, where it is typically used with PLA. To ensure its consistency, PVA should be maintained in airtight, moisture-free containers. High extrusion temperatures lie within 190 and 200°C, as printing above this range can result in nozzle blockages as well as thermal degradation [18].

III. CERAMICS AND GLASS

➢ *Ceramics Material*

Ceramics, which are inorganic and nonmetallic solids consisting of metal, nonmetal, or metalloid atoms, are usually manufactured using the clay that is subjected to kiln sintering [19]. Additive manufacturing (AM) eradicates the need for mould-making and enables financially efficient short-run manufacturing of ceramic materials, like silicon carbide (SiC). This competency is exceptionally valuable in aerospace uses, like jet and rocket engines, in which mass-efficient and high-output ceramic structures with sophisticated geometries are significantly advantageous [8]. Several AM methods, such as binder jetting, material extrusion, and stereolithography, are implemented in ceramic fabrication. For instance, stereolithography can incorporate a mixture of aqueous ceramic paste, photopolymer resin, and ceramic powder to develop porcelain elements. After printing, certain types are typically cured, fired, and glazed to attain mechanical performance compared to injection-moulded products, applicable to fine-detailed designs like fine cavities and undercuts. By removing the demoulding procedure and corresponding inefficiencies, such methods minimise total manufacturing costs.

The incorporation of AM for sophisticated ceramics is evolving from specialised, low-volume parts to larger-scale, client-specific production. Entrepreneurial ventures like Kwambio have improved binder jetting technologies for ceramic powders, making accurate layer-by-layer fabrication possible at minimal material costs [19]. Additional developments include Stoneflower3D’s system from Munich, suitable for processing ceramics, porcelain, plaster of Paris pulp, wax, and edible materials and even applying paints or solder paste [19], with Olivier van Herpt’s clay 3D printer that integrates an engineered extruder and ceramic filament [19]. In medical and biological sciences, Lithoz has rolled out its patented Lithography-based Ceramic Manufacturing (LCM) process, suitable for producing medical-grade tricalcium phosphate for osseous replacement, as well as controlled-run series of complex prototypes [20]. Likewise, Admatec Industries biomedical-grade hydroxyapatite ceramics and forms components depending on zirconia, alumina, fused silica, and aluminium-toughened zirconia, with silica solutions in investment casting [19]. Moreover, online platforms like Shapeways and iMaterialise offer the capability to access food-safe, recyclable, and waterproof ceramic products, including household items such as cups, plates, figurines, and decorative objects [19].

➢ *Glass Material*

Several AM methods are used in glass processing, such as SLS, which fabricates 3D objects by partially melting layers of glass powder with lasers. This technique has practical applications in areas like optoelectronics, architecture, and product design. Fused quartz glass, in particular, is widely applied for optical systems, communication devices, electronic components, and hermetic sealing. As a result of its superior optical transmissivity and thermal stability [8].

Material extrusion has also been researched for glass AM. A method created at MIT causes the extrusion of molten glass at temperatures up to 1640°C via a ceramic nozzle, developing honey-like flows that harden into transparent structures [22]. This technique provides potential for embedding fibre optics directly within printed glass facades, broadening both functional and design usage [8]. Likewise, Micron3DP has established glass printing systems suitable for generating borosilicate and soda-lime glass components at high-capacity processing temperatures [22].

Additional developments include the direct ink writing (DIW) technique developed by Lawrence Livermore National Laboratory (LLNL), which incorporates silica particle suspensions at room temperature to fabricate glass structures. DIW provides the ability to create composition gradients, which are challenging to achieve by conventional means, simplifying and minimising the cost of lens fabrication [22]. Moreover, German researchers have developed “liquid glass” tech, which enables the development of transparent microstructures displaying smooth surfaces and excellent high resolution [23]. Together, these developments emphasise improving the role of AM in glass production, incorporating high-performance engineering demands with architectural as well as aesthetic possibilities.

IV. METALS

Metal additive manufacturing has established itself as a pioneering force in today’s manufacturing landscape, drawing notable attention at industry events such as the Pacific Design & Manufacturing Show [24]. The surge in interest is driven by the ability of metal 3D printing to

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fabricate entirely functional end-use components for continuous manufacturing, reaching well past its earlier role pertaining only to prototyping [25]. With these techniques, highly complex, compact, and performance-optimized geometries can be developed directly, usually using minimal waste and fewer assembly steps when contrasted to conventional subtractive or casting techniques.

Several key processes dominate the field of metal additive manufacturing, including Electron Beam Melting , Direct Metal Laser Sintering , Selective Laser Sintering , Laser Metal Fusion , and Direct Energy Deposition [25]. While each technique varies in terms of energy input, material feed, and processing conditions, they share a common foundation: the layer-wise fabrication of dense, functional metallic parts.

Fundamental materials for metal AM are usually available as wire filaments or atomized metal powders, with the choice relying mainly on the particular procedure employed. A large assortment of materials is a vast selection of these systems, such as stainless steels, copper alloys, aluminum, titanium, and correlated forms, as well as ultra-high-performance alloys [8]. he availability of precious metals—including silver, palladium, platinum, and gold—in powder form further enhances the applicability of the technology [8].

Among the powder-bed fusion techniques, DMLS and SLM are highly significant. Both methods make use of high-powered lasers to precisely scan and fuse regions of a metal powder layer, sequentially building the component from its base. Although capable of generating intricate geometries, such techniques can manufacture components exhibiting varying levels of porosity, impacted by processing parameters and the feedstock quality parameters [27]. Unlike other techniques, EBM operates with a high-energy electron beam in a regulated vacuum chamber to process metal powders like titanium and stainless steel. This method causes components with highly low porosity, a prime advantage for aerospace uses where structural reliability under high thermal and mechanical stresses is essential [8].

- *Titanium*

Titanium, especially the Ti-6Al-4V alloy (Ti64), is among the leading metals in AM. itanium is widely used in metal additive manufacturing due to its excellent strength-to-weight ratio, biocompatibility and corrosion resistance [27]. It is commonly deployed in binder jetting and powder bed fusion techniques, with utility extending throughout the automotive, aerospace, machining, and medical areas. In healthcare, its interoperability allows for the fabrication of custom-fit implants and prostheses. But titanium in powder form demonstrates increased reactivity, subject to processing under an inert gas atmosphere, like argon, or within a vacuum to lessen the chance of fire [27].

Depending on the AM process used, the surface characteristics of 3D-printed titanium can differ significantly. For example, laser-sintered elements typically present a matte-gray and delicately textured appearance, wherein additional finishing methods can optimize these surfaces into a satin-like sheen [28]. In high-performance aviation and space applications, titanium wire feedstock is regularly handled through Electron Beam Melting (EBM) to develop crucial components such as jet engine turbine components [8].

Industrial integration of titanium AM is firmly established. General Electric (GE), for example, successfully integrated a 3D-printed titanium fuel nozzle into its CFM LEAP engines, merging 18 conventional welded components into one lightweight and higher-strength component [29]. Likewise, Airbus Group, in conjunction with EOS, formed titanium nacelle hinges, supplying a 40% decrease in fuel consumption in contrast to their traditional counterparts [29]. In medical science, titanium AM has promoted the production of cerebral implants in Argentina via trabecular titanium and the reassembly of a farmer’s skull in China via patient-specific titanium mesh [29].

Apart from these technical usages, titanium AM has additionally grown into a wide range of fields. Notable examples include 3D-printed titanium horseshoes for competitive motorsports in Australia, modern sculptures created by artist Hugo Arcier, and specialized bicycles built by Empire working alongside Renishaw [29]. Titanium’s hypoallergenic characteristics also make it highly compatible with fine jewelry, while Bugatti has harnessed the material to design compact brake calipers [28].

- *Stainless Steel*

Stainless steel is commonly employed in AM because of its remarkable resistance to corrosion, mechanical strength, and durability under strenuous circumstances. When processed via Electron Beam Melting (EBM), stainless steel powders can be modified into dense, sturdy components. Stainless steel powders are resistant to extreme conditions. Like deep-sea operations, nuclear reactors, and aerospace propulsion systems [8]. Other commonly employed methods for stainless steel additive manufacturing include DMLS and SLM. From the options provided, 316L stainless steel, which is also called 1.4404, distinguishes itself as a preferred option. This low-carbon alloy offers the best corrosion resistance, maximum ductility, and strong thermal stability [30]. Attributable to these properties, 3D-printed 316L stainless steel is widely implemented in tooling applications, mechanical components, and food-safe products in which material reliability and performance are essential [30].

- *High-Performance Alloys*

Nickel-based superalloys, such as Inconel 625, 713, and 718, are extensively utilized in additive manufacturing due to their exceptional capacity to withstand extreme environments [8]. Notably, Alloy 625, a nickel-chromium alloy reinforced with niobium and molybdenum, depicts excellent resistance to high chemical exposure and thermal creep deformation [31]. Such characteristics cause nickel-based superalloys to be pivotal in industrial operations like oil and gas, marine engineering, and aerospace, where they

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are routinely utilized in turbine engines, exhaust assemblies, and fuel system components [8].

Cobalt-chrome alloys, which are Co28Cr6Mo (2.4723), stand as another notable class of materials in AM, providing superior hardness and maximum temperature resistance when compared to titanium as well as stainless steel [8]. Their performance under extreme loads and thermal conditions causes them particularly apt for critical aerospace applications like jet engines and turbine blades. Cobalt-chrome alloys are also widely utilized in medical applications for orthopedic implants, such as knee prostheses and hip, due to their excellent biocompatibility as well as resistance to wear [35].

- *Aluminum*

Aluminum has become a key material in AM, particularly within the aerospace and automotive sectors, because of its weight-efficient design, mechanical strength, and cost efficiency [8]. With the help of methods like DMLS or SLM, fine aluminum powders can be melted layer by layer to fabricate complicated geometries. Such printed components repeatedly indicate a matte, slightly roughened finish, which contrasts with the smoother surfaces. Regularly sourced from traditional milling [8].

Among the frequently utilized aluminum alloys, AlSi10Mg stands out as significant. This alloy gives rise to components with exceptional hardness, maximum dynamic strength, and structural uniformity, generally approaching a pore-free state. It also effectively integrates with post-processing techniques like polishing, machining, and heat treatments [32].

A further notable alloy, AlSi9Cu3, presents a combination of strength, chemical resistance, and maximum thermal conductivity, causing it to be apt for prime automotive components, such as engine components, cylinder heads, and transmission housings [32].

For aerospace industries, AlMgSc (commonly called Scalmalloy®RP) has achieved recognition. This alloy is engineered using magnesium, scandium, and aluminum to deliver outstanding strength-to-weight ratios, with its mechanical characteristics Further refined following hardening treatments [32].

- *Precious Metals*

The adoption of metal additive manufacturing in premium products has allowed for the fabrication of complex, handmade jewelry composed of precious metals[8]. With the help of techniques such as DMLS or SLM, extremely fine particles of these metals are selectively capable of being melted to develop highly intricate designs that cannot usually be realized through traditional manufacturing techniques.

Along with the direct printing, certain methods include indirect manufacturing, in which wax models are 3D printed and then harnessed for lost-wax casting in metal [10]. In order to improve traceability and minimize material waste, systems like the Cookson Gold & EON precious metals AM Platform leverage cartridge-based distribution techniques [34]. With the exactness provided by AM, jewelry designs can now integrate interlaced structures, hollow interiors, and even mechanically operational features that were earlier inaccessible [8].

V. FUTURE MATERIALS

- *Multi-material Shape Memory Polymer*

4D printing builds upon modern breakthroughs in AM, implementing materials capable of altering their shape with respect to time in response to particular external stimuli. A key development in this field was recorded in *Nature* by researchers from MIT and SUTD, who engineered a multimaterial 4D printing technique depending on Designed for Shape Memory Polymers (SMPs) [39]. These polymers exhibit the exceptional capability to deform under bending or high-pressure conditions and subsequently return to their original configuration when in contact with heat. This functionality supports the fabrication of components that adjust in response to conditions in varying operational environments, providing developing applications in robotics, biomedical devices, and aerospace systems where adaptability and flexibility are indispensable [39].

- *3D Printing Molecules*

Scholars at the University of Illinois, guided by Dr. Martin D. Burke, have introduced a molecular 3D printing technology capable of producing new small organic compounds [39]. The technique integrates a modular strategy where about two hundred prefabricated molecular building blocks are chemically “welded” together in modifiable setups. By implementing automated assembly, this innovation enhances the pace of the synthesis of billions of unique molecules, substantially promoting the discovery of new drugs and the formulation of advanced chemical materials. The technology is at present commercialized by REVOLUTION Medicines, Inc., with the objective of improving molecular innovation and quickening pharmaceutical testing [39].

- *3D Printing Conductive Materials*

Authors at Virginia Tech have revealed the application of microstereolithography to fabricate conductive 3D objects at the millimeter scale [39]. The process incorporates a uniquely designed conductive polymer improved with an ionic liquid, which substantially boosts its performance. This improvement makes possible the direct printing of electronic parts, integrated conductive circuits, and even scaffolds for tissue engineering, in which embedded electrical stimulation can serve to bolster and enhance cellular growth [39].

- *3D Carbon Nanotubes*

AM has further initiated the integration of carbon nanotube (CNT) technology, enabling new potential for advanced material development [40]. In this technique, carbon nanotube ink is deposited on conventional plastic filaments and operated through Fused Deposition Modeling (FDM). Upon completion of printing, microwave treatment

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is utilized to connect and reinforce the structure. This method markedly strengthens the strength-to-weight ratio of the final product, making it well-suited for rigorous applications in aerospace, defense, and high-performance consumer goods [40].

➢ *3D Printing Graphene*

Pertaining to advanced nanomaterials, Haydale Graphene Industries in the UK has designed PLA filaments reinforced with graphene for AM [41]. Compared with standard polymers, these filaments offer high strength, stiffness, and total material performance. Graphene-based aerogels produced via 3D printing have displayed extraordinary lightness, with a density of less than 160 g per cubic meter, leading to their being approximately 7.5 times lower in density than air [41]. On account of these unique features, such materials demonstrate notable potential for applications in thermal insulation, energy storage, and filtration technologies [41].

➢ *3D Printing Cemented Carbide*

The Fraunhofer Institute for Ceramic Technologies & Systems (IKTS) has implemented binder jetting technology for the 3D printing of cemented carbide. This method supports the development of components with extraordinary hardness and wear resistance, equipped to resist considerable mechanical stresses. Moreover, the approach enables the fabrication of complicated internal geometries, like integrated cooling channels, rendering it particularly appropriate for applications in drilling, heavy manufacturing, and tooling sectors [39].

➢ *3D Printing of Cellulose*

In partnership with multiple universities, the VTT Technical Research Centre of Finland is advancing the application of cellulose-derived materials in AM. This initiative makes use of the environmental improvements associated with cellulose, incorporating its renewability and biodegradability to support applications in textiles and urban development solutions. Through the utilization of these sustainable characteristics, cellulose-derived filaments may serve as a substitute for petroleum-based polymers, delivering environmentally conscious alternatives for 3D printing throughout various industries [42].

➢ *4D Bio-Inks*

Recent breakthroughs in biofabrication have implemented 4D bio-inks, which incorporate shape-morphing performance integrated with biocompatibility [37]. These cutting-edge materials adapt to environmental stimuli like temperature, moisture, or pH, enabling the development of dynamic tissue structures capable of shape transformation after printing. Such progress demonstrates notable potential for the progression of regenerative medicine, with expected developments in responsive tissue engineering, adaptive prosthetics, and self-assembling implants likely to occur over the next decade [38].

➢ *3D Printing Materials History*

- *The Starting Stage*

The development of additive manufacturing started in 1981, when Dr. Hideo Kodama presented the first completely functional rapid prototyping (RP) device depending on thermoset polymer resins. Rolled out the first fully operational soft or viscous state [46]. In 1984, Chuck Hull secured a foundational patent application for stereolithography (SLA), a method that uses UV light to cure photopolymer layers progressively. By 1988, S. Scott Crump had constructed Fused Deposition Modeling (FDM), an unconventional extrusion approach later introduced commercially via his company, Stratasys [47].

In the first half of the 1990s, scholars at MIT originated powder bed and inkjet 3D printing by using powdered ceramics, starch, and gypsum materials that were initiated through liquid binders like water. Between 1994 and 1998, the technology progressed to support wax materials for complex modeling and the deployment of titanium alloy powders in aerospace assemblies through inkjet print head mechanisms [47].

- *The Middle Stage*

Over the period 1999–2010, 3D printing developed beyond basic prototyping to allow innovative applications, especially in the medical field. A significant milestone occurred in 1999 when the Wake Forest University fabricated artificial bladder scaffolds using 3D printing and seeded them with a patient’s own cells, thereby avoiding adverse immune responses. These scaffolds constituted the initial demonstration of 3D-printed human organs transplanted into patients [49].

The decade experienced further remarkable progress, such as the fabrication of the first operational miniature kidney and the development of prosthetic legs using complex mechanical characteristics, as well as the bioprinting of blood vessels from human cells [50]. Together, these developments formed the basis for the medical promise of AM and fostered additional studies into biocompatible materials and regenerative medical solutions.

- *The Present Stage*

Beginning in 2011, 3D printing has grown into a flexible production platform, supporting the creation of objects using a broad spectrum of materials, including plastics, metals, glass, wood, paper, and composites [49]. Today’s applications extend to personalized apparel, jewelry, household items, and musical instruments. Moreover, technological innovations, including 3D-printed homes, vehicles, drones, edible products, and bioengineered structures, increasingly obscure the boundary between standard manufacturing technique and rapid, tailored production.

Developing technology demonstrates potential in flexible displays, nanofluidic filters, microscale cameras, and rollable, portable batteries, signaling a dynamic future for nanoelectronics. Emerging breakthroughs in advanced

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materials are likely graphene, carbon nanotubes, lithium iron, living cells, and remaining nanomaterials—Will advance the next generation of 3D printing applications [51]. This sustained development shows that the advancements in 3D printing are continually driven by new material discoveries, which open up long-term possibilities.

VI. CONCLUSION

This review has exhibited the full range of materials able to function with leading AM techniques, such as metals, polymers, ceramics, concrete, chocolate, and living cells. In several physical forms, including liquids, powders, and filaments. As materials research advances, AM is progressively aligned for integration into standard manufacturing supply chains, empowering durable and high-strength industrial solutions. The market pressures are predicted to drive faster adoption, minimized equipment costs, and enhanced processing techniques, contributing to lower material expenses.Prospective innovations in advanced materials such as cellulose, graphene inks, and 4D bio-inks promise to permit the development of complex, operational products. These advances in this area may lead to highly automated, next-generation manufacturing systems, a breakthrough formerly considered unattainable.

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