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REVIEW ARTICLE

3D printing for ultra-precision machining: current status, opportunities, and future perspectives

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ABSTRACT Additive manufacturing, particularly 3D printing, has revolutionized the manufacturing industry by allowing the production of complex and intricate parts at a lower cost and with greater efficiency. However, 3D-printed parts frequently require post-processing or integration with other machining technologies to achieve the desired surface finish, accuracy, and mechanical properties. Ultra-precision machining (UPM) is a potential machining technology that addresses these challenges by enabling high surface quality, accuracy, and repeatability in 3D-printed components. This study provides an overview of the current state of UPM for 3D printing, including the current UPM and 3D printing stages, and the application of UPM to 3D printing. Following the presentation of current stage perspectives, this study presents a detailed discussion of the benefits of combining UPM with 3D printing and the opportunities for leveraging UPM on 3D printing or supporting each other. In particular, future opportunities focus on cutting tools manufactured via 3D printing for UPM, UPM of 3D-printed components for real-world applications, and post-machining of 3D-printed components. Finally, future prospects for integrating the two advanced manufacturing technologies into potential industries are discussed. This study concludes that UPM is a promising technology for 3D-printed components, exhibiting the potential to improve the functionality and performance of 3D-printed products in various applications. It also discusses how UPM and 3D printing can complement each other.

KEYWORDS ultra-precision machining, 3D printing, additive manufacturing, future perspectives, start-of-the-art-review

1 Introduction

Ultra-precision machining (UPM) and 3D printing are two emerging technologies with immense potential for development due to the high demand across various fields in artificial intelligence (AI), the electronics industry, biomedicine, optics, and electricity. UPM operates in accordance with the principle of subtractive manufacturing, achieving nanoscale machining accuracy through methods, such as milling, grinding, and polishing. Meanwhile, 3D printing is based on the principle of rapid prototyping and additive manufacturing (AM). It uses a broad spectrum of materials to fabricate a range of precision parts. With its advantages of intelligence, automation, capability to generate complex structures, and saving materials and time, 3D printing technology offers benefits that traditional manufacturing processes lack. Consequently, it has been adopted by numerous universities, hospitals, companies, enterprises, and research institutions. However, although various 3D printing technologies are currently available, they generally face challenges with regard to being applied directly as products in various industries, such as low printing and shaping precision, poor surface quality of printed specimens, and visible printing marks. Therefore, the integration of 3D printing and UPM technologies has been proposed. This concept originates from the need for

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post-processing treatment of 3D-printed products. However, with the deep integration of the two technologies, applying UPM to 3D printing cannot only enhance the accuracy of 3D-printed products but also endow them with micro/nano-level composite structures and optical surfaces, among other special morphologies. This feature broadens the application of 3D-printed products across all major fields. In this regard, this study delineates the prominent characteristics and origins of UPM and 3D printing technologies. It also elaborates on the advantages and applications that originate from the fusion of the two technologies and provides an assessment of the prospective evolution of this technological integration. The objective of this study is to leverage the capabilities of advanced manufacturing and machining technologies to propel industry progression and bridge existing gaps in associated research fields.

1.1 Introduction to UPM

1.1.1 Background of UPM

Material removal processes are crucial for manufacturing and utilized for producing various mechanical components with high quality in accordance with stringent specifications [1]. Precision machining is a subtractive manufacturing technique that utilizes advanced tools, programming, engineering techniques, and equipment to remove materials from raw products and produce high-quality, repeatable, accurate, and durable finished assemblies [2]. UPM encompasses cutting, grinding, polishing, and unconventional machining [3], which are essential technologies for achieving the highest form and surface quality, with machining accuracy of up to 0.1 nm and surface roughness of less than 10 nm [3]. Typical machines, such as lathes, lasers, mills, and electrical discharge machines from Switzerland, the United States and Germany, are frequently used to manufacture products in UPM [1]. The cutting mechanism distinguishes UPM from macro-machining, wherein the cutting mechanism involves shearing the material to form a chip. By contrast, the cutting mechanisms in UPM are more complicated [4]. UPM has emerged as a reliable machining technology for fabricating precision components in various industrial applications, including lasers, optics, electronics, aviation, and vehicles. Furthermore, UPM is widely used in the aerospace, automotive, electronics, medical, and semiconductor industries despite its limited applications within the scientific community [3]. For example, diamond machining, which is a type of UPM, is particularly effective in producing optical surfaces with microstructures that are frequently challenging to create using conventional techniques [5]. Even a slight error distribution can significantly affect the precision level of UPM [6]. Moreover, UPM also plays a crucial role in generating microstructures on various material surfaces. Meanwhile, other techniques, such as focused ion beam (FIB) [7] and five-axis machine tools [8], have also been developed and integrated into UPM in recent years. However, UPM faces limitations, such as slow removal rates [5] and sustainability concerns [9]. To address these limitations, several studies [9–11] have been conducted to align UPM with the triple bottom line concept. Simultaneously, recent technological advancements, increased demand for precision components in advanced technological products, and groundbreaking research findings have raised the demand for precision machining. According to recent market research [12], the market size of the precision machining industry in 2020 was estimated to be USD 11.8 billion, with a compound annual growth rate of 6.6% until 2028. This growth has led to advancements in micromachining techniques that address the need for accuracy, precision, and material development across various industries. During the 1990s, UPM significantly affected the development of industries, such as automotive, information technology, optoelectronics, and communication [3].

1.1.2 Cutting tools used in UPM and their importance

UPM utilizes cutting tools made of diamonds, with surface roughness reaching several nanometers [3] and precision level reaching the nanoscale; UPM has found numerous applications [5]. However, UPM is susceptible to several variables. To utilize cutting tools effectively, one must understand the characteristics of various UPM factors, particularly tool materials and their properties and geometries, tool wear mechanisms, and processes for controlling tool wear [13]. Moreover, tools used in UPM must meet stringent requirements, such as thermal stability, cooperative to precision spindle bearings and linear guides, and high resolution of linear and rotary motions [14]. Diamond tools are commonly used in UPM due to their cutting ability for metals and ceramics [15], high tensile strength, precise machining capability, high thermal conductivity, low friction, and high wear resistance [16]. Single-point diamond turning is a representative diamond-based cutting technique wherein the rotation of the workpiece generates the cutting motion with a diamond tool while the tool moves relative to the surface [14]. The theoretically rounded cutting-edge radius of a diamond turning tool can be as small as 3 nm [3]. Another standard tool used in UPM is the micro-milling tool, wherein the tool rotates while the workpiece is moved by a relatively translational or rotational motion to achieve a constant cutting velocity and create complex optical geometries, shapes, and structured surfaces [14,17].

To achieve the specific manufacturing objectives of UPM, several researchers have developed UPM and relative cutting tools with the assistance of other devices. For example, intermittent diamond cutting was introduced as an innovative machining technique for enhancing the machinability of titanium alloys without requiring complex equipment to improve the machinability of these alloys and simultaneously facilitate the precision level of their components and UPM [9]. Ding et al. [7] achieved a cutting edge length of 25 m and smooth face quality by using FIB to sputter a diamond block into a 3D cutting tool shape. The fabrication of microstructures in brittle materials, such as ceramics, by using ductile mode machining [4] is another potential growth area for UPM. When such materials are machined below a critical depth of cut (DOC), high-quality surface without pitting or cracking can be obtained. By using this method, ceramic materials can be machined by decreasing DOC and/or increasing cutting speed [4]. These tools are used for machining ferrous materials, improving lubrication and cooling, and reducing cutting force in UPM. Numerous studies have highlighted the significance of cutting tools, particularly those made from diamonds and other materials, in UPM and their influences on generating excellent surfaces during machining.

1.1.3 Surface generation and its mechanism in UPM

Surface generation in UPM involves the removal of material with a cutting tool to create a surface on a workpiece [18]; it is critical for determining the functionality, durability, and quality of the final product. In UPM, surfaces produced typically exhibit nanometric surface roughness and sub-micrometric form error [19]. Surface roughness refers to irregularities or deviations in a material's surface texture; it is measured by the average deviation of the surface from its ideal form [20]. Form error refers to the deviation of the surface from its intended shape or form, such as a flat surface that is not perfectly flat [20]. Various processes can be used for surface generation, including grinding, turning, and milling. However, the machining complexity of UPM means that even small changes in variables can significantly affect surface quality [18]. The cutting mechanism of a tool exerts a significant effect on surface generation in UPM.

Changes in cutting parameters affect the interaction between the tool and the workpiece, leading to variations in vibration levels and surface quality [21,22]. The material and shape of a tool can also influence vibration and the resulting surface quality. Moreover, machine tool structure and dynamics can affect the stability and vibration levels of the cutting process [21]. Several factors influence surface finish, including the shape of the tool insert nose and edge radius [23]. Surface finish is primarily controlled by the edge radius when specific conditions are met [24,25]. Spindle vibration is another essential factor that influences surface generation, because irregular spindle vibration waves can produce patterns on the machined surface [26]. In single-point diamond turning (SPDT), which is a representative UPM technique, the relative vibration between the tool and the workpiece in the cutting force direction significantly contributes to surface generation [27]. Elastic recovery [20] and material swelling [27] also affect surface finish. In addition, the employed cutting strategy can significantly influence the surface quality and form accuracy of free-form surfaces. The spiral-cutting strategy can reduce surface roughness and improve form accuracy [28]. By contrast, a compensation strategy for the inverse kinematics of machine tools effectively reduce the form error of free-form surfaces [29]. Selecting appropriate cutting conditions and strategies is crucial for achieving high-quality surfaces in UPM [30]. Overall, machine tools, motion accuracy, cutting conditions, tool geometry, material properties, vibration, and other variables influence surface generation in UPM [18,19,21,29].

1.1.4 Simulation modeling and AI in UPM

Simulations are widely used in UPM to predict machining outcomes and factors, such as surface roughness, chip formation, surface topologies, and cutting forces [30]. They are also employed to study the effect of workpiece characteristics on machining mechanisms [31]. Numerical simulation methods in UPM support experimental studies [31] on determining optimal machining parameters and reducing the need for trial-and-error experimentation, decreasing machining costs and saving time by providing efficient results [31,32]. However, theoretical models can only provide relatively accurate findings due to numerous variables involved in modeling UPM processes [30]. Accurately predicting a UPM process, with its multiple physical phenomena and factors, such as heat transfer, material anisotropy, cutting behavior, chip formation, cutting tool geometry, machine tool dynamics, and cutting parameters, poses a significant challenge [30,31]. Various computational strategies are employed to overcome these restrictions. Molecular dynamics (MD), the simulations of which can provide the deformation behavior of materials at the atomic scale and insights into cutting mechanisms, is one strategy that investigates the behavior of atoms and molecules over time [16,33]. By examining material deformation mechanisms and their dependence on intrinsic microstructural characteristics and extrinsic machining parameters, MD simulations can deepen the understanding of surface generation in UPM [16]. Furthermore, MD has been proven to be a valuable tool for simulating the nanometric cutting of nano-twinned copper [33] and investigating subsurface damage in high-entropy alloys [33], and the ion implantation modification of cubic SiC [34] and brittle materials [35]. In addition to MD, finite element modeling (FEM) is another widely used simulation method in UPM [36].

FEM divides a system into smaller finite elements and solves separate equations for each element [36]. Relevant studies have demonstrated that the use of multi-scale and multi-physical field modeling and simulation methods can intuitively identify the coupling of different energy fields during UPM and optimize the accuracy and efficiency of UPM in various materials [37, 38]. Notably, the effects of magnetic and ultrasonic fields on ultra-precision turning [39] and grinding [40] have also been confirmed further. Recently, machine learning and AI approaches have been used to optimize the machining process. For example, Basheer et al. [41] used experimental data to construct an artificial neural network (ANN)-based model to predict surface roughness in precision machining with a correlation value of 0.977 and a mean absolute error of 10.4%.

1.1.5 Applications of UPM

Precision machining techniques have evolved over the years to meet the demands of various industries. Initially developed in the 1950s for aerospace and national defense applications [3], UPM techniques, such as diamond turning, were used to fabricate reflective mirrors for laser fusion and components for missiles and aircraft [3]. Since then, UPM has been widely adopted as the need for ultra-precise molds, lenses, wafers, laser scanners, and DVD players grew across industries, including energy, optoelectronics, and medicine [3,5]. Even with minor machining equipment errors, the performance of these component can vary significantly [5], highlighting the importance of precision in these fields [6]. UPM has also been crucial in advancing personal computers and electronic equipment, because it has been used to produce computer memory discs and printer components [42]. Major corporations, such as Philips of the Netherlands, have developed highly innovative machining technologies “in-house” to capitalize on opportunities in markets, such as the compact disc player market. Moreover, the use of brittle materials, such as silicon, glass, quartz crystal, and ceramic, has increased in microelectromechanical devices. One method for machining these brittle materials is ultrasonic vibration-assisted ultra-precision cutting, which involves using an amplitude of 25 μm or less and a frequency range of 20–100 kHz [4]. For example, micro-lens structures can be obtained by rotating and machining on the surface of a silicon platform with a diamond tool [4]. Furthermore, the demand for optics with free-form geometries is growing, frequently necessitating raster fly cutting or grinding depending on the material [42]. Advanced laser printer optics exemplify such geometries [42].

In addition, creating micro patterns and microstructures is an intriguing application of UPM [4]. Various microstructures, including microgrooves and microarrays, can be fabricated on flat and curved surfaces by feeding a rotating cutting tool in one direction relative to the workpiece [4]. UPM is commonly utilized in producing Fresnel lenses, also known as diffractive elements in optics [43]. Initially used in lighthouses [44], Fresnel lenses currently play a crucial role in optical communications and information processing, optical vortex transmutation, optical imaging systems, and photonic devices due to their compact size, light weight, and exceptional optical performance [45]. The diamond micro-scraping technique has been introduced to enhance the overall performance of a Fresnel lens array; it can effectively solve the challenge of machining polygonal Fresnel lens structures in a roller mold [43,44]. Meanwhile, a promising emerging technique called diamond micro-scraping has been developed to overcome these limitations. This technique has been validated using a five-axis ultra-precision machine system [46]. Through theoretical analysis, numerical simulation, and experimental research, the fuel nozzle can be machined using abrasive flow machining technology, which is particularly effective in producing the complex cavities and inner channel surface required for an engine fuel nozzle; then, magnetic particles are incorporated [46].

1.2 Introduction to 3D printing

1.2.1 Background of 3D printing technology

3D printing, also known as AM, was initially commercialized by Charles Hull during the 1980s [47] as a material-oriented manufacturing method for a wide variety of structures and complex geometries from digital models created using computer-aided design software [25,48], which further generates a unique file type sent to a 3D printer with three distinct manufacturing properties: additive, 3D, and layer-based [49]. Then, the 3D printer produces the component by placing successive layers on one another; that is, 3D printers read the parts one 2D layer at a time instead of a complete part [48]. Initially, AM was predominantly employed by architects and designers to produce functional prototypes [25]. However, the rapid development of AM materials and techniques has resulted in the widespread application of AM in various industries, such as aerospace, biomedicine, fashion, nuclear, electronics, and robotics [48].

The unique advantages of AM are minimal material waste and cost-effectiveness, which place 3D printing as a technology of the future [49]. However, the precision of manufactured parts highly relies on the appropriateness of the employed method and the scale of printing [25]. For example, microscale AM presents challenges in surface finish, layer bonding, and resolution, frequently necessitating post-processing, such as sintering [25]. Another consideration of 3D printing is the formation of voids between material layers, resulting in low material density.

Moreover, the manufacturing process is typically more time-consuming than conventional techniques.

The field of AM encompasses two major types: extrusion and laser-based AM [50]. In extrusion-based AM, a heated nozzle melts and deposits the material during extrusion. Then, the material is cooled and solidified to form the final component. Fused deposition modeling (FDM) is one of the most common extrusion processes; it utilizes polymer filaments to create 3D printing material layers [25]. Meanwhile, a laser-based process is employed to melt, solidify, and cure the powdered material supplied to the processing head [50]. Powder bed fusion (PBF) is a widespread technique under this AM category; it is capable of producing high-quality and fully dense objects [51]. In PBF, a thermal source, such as a laser, induces fusion between powder particles, followed by adding and smoothing another powder layer by using a roller or blade [52,53]. Other standard AM techniques, such as stereolithography (SLA), selective laser sintering (SLS), binder jetting (BJ), direct energy deposition (DED), and laminated object manufacturing (LOM) [48,49], are appropriate for specific materials. Currently, plastics and polymers dominate the market for 3D printing, with approximately 30000 machines in production [50]. For example, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the most commonly used polymers in the AM of composites [25]. However, the materials used in 3D printing are not limited to traditional materials, because this technique can be applied to metals, ceramics, concrete, and intelligent materials [47]. Innovative materials, which can alter shape and geometry in response to external factors (e.g., heat and water [47]), have applications in self-evolving structures, soft robotics systems, and shape-memory alloys, such as nickel–titanium [48].

With the advancement of technology, 3D printing has been incorporated into nearly all engineering fields. Current AM technologies enable the fabrication of electronic components that range from capacitors to resistors and inductors [52]; biodegradable polymers [49]; bone and heart valve scaffolds [48]; bone, cartilage, and knee implant printing [54,55]; and other industry-specific innovations. For example, the National Aeronautics and Space Administration (NASA) of the United States reduced costs by 65% by using selective laser melting (SLM) to minimize the number of welds and potential rework during the production of its rocket engines [48]. Boeing and GE Aviation redesigned GE90-94B jet engines by incorporating more than 400 3D-printed components [56]. In addition, WinSun 3D, a leader in 3D printing technology, has applied the technology several times to produce inexpensive houses in Shanghai by using cement and glass fiber [25].

Furthermore, the advancements in 3D printing technology have positioned it as a critical player in the Industry 4.0 era due to its vast potential to revolutionize manufacturing processes across multiple industries. Instead of being viewed as a stand-alone process, AM should be an integral part of multi-process systems that pave the way for developing novel materials and fulfilling new product requirements [52]. The numerous benefits of AM, such as digital data transfer, remote access, and minimal human intervention, contribute to achieving Industry 4.0 fundamental goals [57]. Moreover, 3D printing technology contributes equally to "green" or sustainable manufacturing [58]. Paszkiewicz et al. [59] proposed a framework that facilitates the development of functionally and geographically feasible prototyping systems; this framework can be seamlessly incorporated into Industry 4.0. The sequential and cross-layer framework enables information exchange between layers to enhance overall infrastructure efficiency. As one of the critical pillars of Industry 4.0, 3D printing is crucial for establishing cloud manufacturing as a revolutionary production mode with the potential to replace conventional mass production methods [56].

1.2.2 3D printing for traditional machining

Traditional machining processes, such as milling, turning, grinding, and cutting, are commonly employed to extrude the unnecessary parts of a material. However, these subtractive machining techniques face challenges when dealing with complex shapes [60]. AM provides a solution for designing and operating complex parts through its three primary steps: 3D model design, prototyping, and post-processing [60]. However, Eyers and Potter [61] argued that preprocessing, including feasibility assessments, error checking, and production planning, is essential for successful AM. One of the key advantages of 3D printing is its ability to achieve significant material savings, because it eliminates the need for tools, molds, punches, and human intervention in the manufacturing process [62]. By replacing subtractive technologies with 3D printing, some manufacturers have successfully reduced material waste by 40% [60]. Compared with traditional machining, AM offers more options for structural design in the production of glass products, such as ornaments and jewelry. In addition, the proximity of AM equipment to distribution points enables reduced reliance on international transit [63], making it a valuable resource for protective equipment manufacturers during the COVID-19 pandemic [64]. AM does not only address supply chain challenges, but it also enhances productivity in machining. By using 3D printing concurrently with traditional manufacturing methods, such as producing aircraft engines and other parts, production rates can be increased and assembly time can be reduced [49]. Furthermore, Rouf et al. [56] discovered that the AM of certain aircraft parts can reduce material consumption by 75%.

Varying objectives require the use of different AM techniques in the industrial field. For example, the FDM method simplifies manufacturing processes and improves inherent properties, allowing for competitive prices in the industrial casting of wax and wax forms [49]. The fabrication of lattice and spatial structures is another primary application of 3D printing. In contrast with conventional processes with fabricating complicated structures, 3D printing technologies enable the direct fabrication of lattice structures with controlled porosity [62]. When a component requires a good surface finish and dimensional precision, a nanoscale 3D printing process can be utilized. For example, aerodynamically focused nanoparticle printing was used for material formation, while FIB was used for material profiling [65]. Micro-machining assists and bridges at different scales, allowing the printing of various 3D structures by using metal/ceramic nanoparticles with no solvent or posttreatment technique [65]. Hybrid manufacturing, which combines AM and high-precision processes, is gaining popularity because it allows for producing near-net-shaped components [66].

Another breakthrough in the industrial sector is 4D printing, which allows for individual customization [63,67]. The PBF method and layer-by-layer approach in 4D printing allow sensors to be integrated into any point within a manufactured component [49]. At present, complex electric components can be 4D-printed and seamlessly mounted without sacrificing functionality [48]. Rapid prototyping is another application of 3D printing in industrial manufacturing; it improves communication within the production team and has extensive use in the automobile manufacturing sector [67], because the number of companies that sell AM systems that are compatible with metals has more than doubled in recent years [25]. BMW employs this novel approach to improve the ergonomics of handheld assembly tools, while Hyundai uses AM technologies for inspection, evaluation, and aerodynamic function testing [58]. Similarly, a new start-up called *Kappius* discovered a way to improve the efficiency of bicycle hubs by using laser sintering [68]. However, most existing metal alloys cannot withstand AM processes due to insufficient microstructures formed during the melting and solidification dynamics [25]. Furthermore, in contrast with conventionally manufactured components, 3D-printed parts behave differently due to the unique mechanical and thermal properties of existing materials and technologies. A rare characterization approach was performed to quantify this phenomenon [66].

2 Current status of 3D printing used for UPM

Despite the previously discussed advantages of 3D printing, the widespread industrial use of this emerging technology must still be extended. For example, researchers conducted a case study on a US-based manufacturing company that employed traditional machining for surface finishing despite having cutting-edge 3D printing equipment to produce automobile parts due to defects in 3D-printed materials, such as layer misalignment [49,63,67,69]. Given that AM processes must still be supplemented with subtractive machining, some manufacturers may find it economically unjustified to adopt 3D printing technologies. Furthermore, the desired outcomes have only been achieved in laboratory settings rather than production environments even at the nanoscale level [70]. Commercializing microscale AM processes is challenging due to ex-distribution, geometry, and volume shrinkage factors [70]. SLA and novel 3D printing methods have limitations when achieving complex structures [70]. Material limitations also exist, because 3D printing necessitates low-viscosity resins [71]. The dimensional accuracy and strength of 3D-printed components are influenced by printing technologies, parameters, supporting structures, and post-processing procedures [72]. For example, continuous liquid flow through a nozzle is induced by the direct application of constant displacement or pressure to the liquid in the flow-based direct ink writing process [73]. To preserve the shape of the component, materials used in this method should form a continuous filament with a consistent cross-sectional area upon exiting the nozzle and dry quickly upon contact with the substrate. Consequently, the primary engineering challenge is ensuring a high-density part while avoiding nozzle clogging issues, necessitating the use of materials with low porosity after deposition [73]. In addition to industrial applications, biomedicine benefits from specific soft tissue structures, pore designs, and micro- and nanostructures that provide mechanical and biochemical support for tissue infiltration, integration, and repair functions. These features closely mimic human physiologic systems, enhance the performance of composite structures, and guide cellular interactions. They have significant applications in fracture injury repair, oral gingival repair, cytopathic migration, and other cardiovascular diseases. Consequently, a wide array of 3D-printed implants has been developed, including those made from titanium alloys, ceramics, polymer plastics, and biodegradable polymers. However, these applications also encounter challenges related to precision, material limitations, and constraints imposed by printing parameters and environments [74–76].

Electrohydrodynamic printing, which produces submicron-resolution droplets, is a viable option for microscale AM [73]. However, electrohydrodynamic printing faces significant challenges in manufacturing 3D geometries, including the standoff distance between the substrate and the nozzle, droplet charge accumulation, and issues related to solvent drying. In particular, 3D structures with high aspect ratio require increased nozzle–substrate distance and high electric potentials to ensure stable printing. Electric field distribution significantly affects the precision level of 3D printing in electrohydrodynamic printing. Droplet charge accumulation on nonconductive substrates further affects printing stability, and thus, predicting and modeling printing behavior by using the electrohydrodynamic printing method are difficult tasks [73]. The same limitations exist in the binder jetting process. Compared with the preceding processes, FIB induced deposition (FIBID) can produce components with diverse complex structures [77]. Although it is slower than many other 3D printing methods, the resolution achieved is considerably higher. However, given the technology's complexity, FIBID machines have only been developed by a few companies that are geared toward the needs of the integrated circuit (IC) industry, contributing to a low adoption rate. Traditional post-processing is frequently required when selective laser melting is used to manufacture a component due to the insufficient surface quality generated by these AM methods [70]. Similarly, fused deposition modeling components have low surface quality, resulting in light scattering effects in optical components due to temperature distribution in the nozzle [70]. Conversely, SLA is a 3D printing approach that uses ultraviolet (UV) light, solidifying curable polymer materials [70] and increasing printing speed. However, high-power light sources are required to perform this method, and the lack of control over light energy penetration makes it unappealing to the commercial printing industry. Despite these obstacles, several novel approaches have overcome the majority of 3D printing limitations. One such approach proposes a novel electropolishing-enhanced 3D printing for fabricating high-precision Ti-6Al-4V pentamode metamaterials [78]. Although achieving high precision on pentode metamaterials remains challenging due to strict size requirements, this method significantly lowers the threshold of such intricate structures and achieves a minimum processable size of 100 μm, which is impossible with other high-level 3D printing methods [78]. Another suggested practical approach is obtaining an inferior version via available AM and then performing subtractive secondary processing. Academics have proposed hybrid manufacturing, a combination of AM technologies and traditional machining methods used in component manufacturing [79]. When printing with metal in hybrid approaches, the machine first extrudes metal-infused paste rather than heated plastics after flattening the build surface with a computer numerical control (CNC) machine. After the extrusion of each layer and the solidification of the material via a drying process (which also improves density and minimizes shrinkage), the top layer is milled to ensure good adhesion of the next layer [80], with vacuuming performed automatically during each milling operation to remove machined waste [80]. Another challenge faced by AM and hybrid manufacturing is limited processing capabilities when achieving seamless integration of thermal and mechanical functional properties into microscale components due to surface integrity, anisotropy, and material defects [81]. Plastics with poor material properties, such as heat deflection temperature, elongation of break, brittleness, and aging, which are difficult to control are frequently unsuitable for 3D manufacturing with high precision levels [82]. Some researchers prefer laser-based AM methods, but the commercialization of such methods has been eliminated due to various limitations [83]. Meanwhile, the SLA method, in conjunction with nanoscale deposition, enables the creation of various ceramic structures with feature sizes as small as nanometers. This technique cannot produce fully dense metallic structures. Different AM techniques are summarized in Table 1.

3 Suggestions and opportunities for 3D printing in UPM

In 1980, Charles Hull first commercialized 3D printing, which is widely used in various industries at present [47,86]. Over the years, printing materials have expanded to ceramics, metals, plastics, photosensitive resin, and plaster. Moreover, various 3D printing technologies with distinct characteristics have been developed, including SLS, direct laser metal forming/sintering (DLMF/DLMS), electron beam melting (EBM), laser-engineered net shaping (LENS), FDM, and vat photo-polymerization (VPP) [87,88], as shown in Fig. 1 [89−94]. SLS, DLMS, LENS, and EBM technologies employ lasers or high-energy beams to directly melt and fuse metal-based hybrid powders to produce cutting tools. The density and surface accuracy of the cutting tools are then improved through sintering, cutting, and grinding. Laser and high-energy beam-based 3D printing technologies have received increased attention for processing different metal powders. Previous studies have focused on the fundamental properties of powders and small specimens, while recent research has shifted toward studying the properties of tools themselves, including iron, copper, cobalt, titanium, and SS-316 [95,96]. For example, Gan et al. [97] successfully manufactured CuSnTi-based diamond composite specimens by using the SLM technique and then characterized the relative density, microhardness, wear resistance, and surface morphology of the of the sample. Wu et al. [98] successfully fabricated CoCrMo-based diamond ultrathin saw blades by using the SLS technique and performed mechanical property and rock cutting tests. Similarly, Zhang et al. [86] created a complex gridded pregnant diamond drill bit matrix by using SLS technology.

Meanwhile, FDM technology, which is known for its

Table 1 Comparison of different AM techniques [47,84,85]

AM type	Materials	Definition	Advantages	Disadvantages
Selective laser sintering (SLS) Electron beam melting (EBM)	Paraffin, nylon, and metal materials, including aluminum alloys, cobalt-based materials, nickel-based alloys, stainless steel, titanium alloys, and their composites	An electron beam or laser is used to melt or fuse powder materials to produce components.	It can be used to efficiently print a wide range of materials and multiple parts simultaneously.	Equipment and material costs associated with this technique are high, and the density and surface roughness of the printed specimens are poor.
Laser-engineered net shaping (LENS)			It can manufacture and machine parts with complex curved surfaces without molds.	The printed specimen is prone to cracking due to high internal stress, and its surface accuracy is poor.
Selective heat sintering (SHS)			It eliminates the need for support structures and has low cost.	It takes a long time to print and exhibits poor accuracy.
Fused deposition modeling (FDM)	Polylactic acid, acrylic butadiene styrene, polypropylene, polyethylene, and other composites that contain ceramics or metals	Heating and extruding thermoplastic composites to print layers	It can print parts with complex structures and details and is suitable for small batch production due to low cost.	It has obvious print marks and is not suitable for printing large specimens.
Binder jetting Inkjet powder printing	Polymers, metals, ceramics	Using jet chemical binder onto the spread powder to form a layer	It has a simple process, fast forming speed, and high precision printing for small specimens.	It prints samples with poor mechanical properties that require further post-processing.
Sheet lamination	Paper, plastic fiber composites	It creates objects by stacking multiple layers of foil that consist of thin sheets of materials on top of one another.		
Stereolithography (SLA)	Photopolymer resin, polymers	It refers to the use of laser, light, or UV light to cure photoresponsive polymers.	It has high printing accuracy, a simple process, and a short production cycle. It is mostly used for optics and medical applications.	It has high equipment cost and generates toxic and polluting gases during printing.

environmental friendliness and low cost, relies on using a binder to coat the powder and control the fluidity and buildability of the powder by adjusting temperature to achieve high-precision molding. Subsequent defending and sintering processes further enhance the mechanical properties of the printed products. The method has always been at the forefront of advanced manufacturing and widely utilized by small and medium-sized enterprises due to its cost affordability and simplicity of processing. Initially, only plastics can be printed using fused filament manufacturing, because metal printing requires high temperatures to melt metal powder particles. However, the combination of polymers and metal particles, including stainless steel, cobalt–chromium alloys, Cp-Ti, Ti-6Al-4V, NiTi, Inconel, gold, silver, copper, aluminum, and their alloys, has made metal printing possible [99,100].

Hwang et al. [101] analyzed the effects of printing parameters on the tensile properties of the final product and concluded that metallic polymer filaments can be used for printing metal parts. Gong et al. [102] utilized FDM 3D printing technology to fabricate 316L stainless steel parts and investigated the effects of printing parameters on the mechanical properties and shrinkage of the finished metal parts. These studies have provided valuable practical guidance and references for producing and machining a wide range of ultra-precision tools. VPP technology shares similarities with FDM technology in terms of principles. However, it focuses on the phase change properties of photosensitive resin pairs when exposed to UV light during a molding process. At present, VPP is largely used to manufacture ceramic tools. Given its benefits of high precision, good surface roughness, and excellent performance, this technology has been extensively studied and applied in tool production [103]. Zhou et al. [104] used VPP to manufacture alumina tools with high density. After further optimizing the drying and debonding processes, the relative density reached 99.3%, and Vickers hardness was 17.5 GPa.

As 3D printing manufacturing technology gained recognition for its material-saving, environment-friendly, intelligent, and automated attributes, some researchers have started considering it as a potential replacement for traditional processes in the production of UPM tools, such as carbide, alumina ceramic, diamond, and boron nitride [105,106]. Furthermore, some researchers [87,88] have improved the manufacturing design and quality of

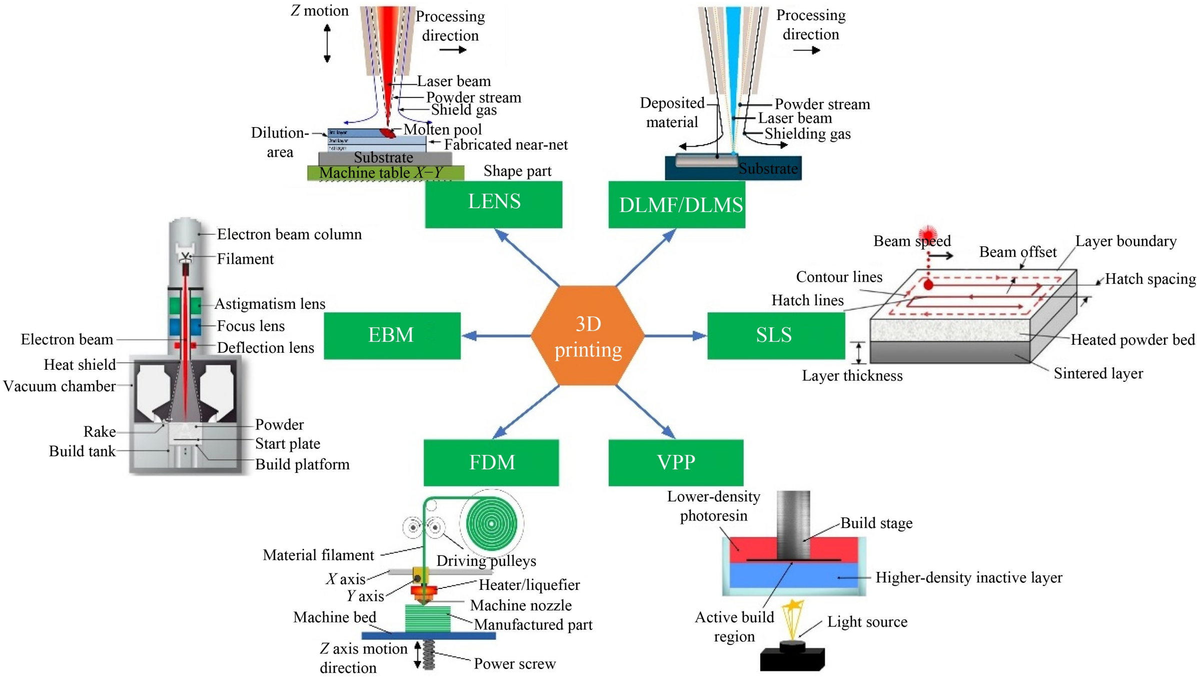


Fig. 1 Current mainstream 3D printing technologies. The listed technologies are collected from Refs. [89–94]. The images quoted above have been rearranged and reprinted with permission.

manufactured parts by combining 3D printing technology with subtractive machining, realizing the concept of integrated production and processing and leveraging the advantages of both technologies for precision manufacturing. The integration of 3D printing and precision machining provides multifaceted applications for manufacturing and opens up new machining directions in UPM.

3.1 3D-printed cutting tools

Numerous researchers in the field of 3D printing have developed various precision cutting tools for iron, copper, aluminum, titanium, tungsten, cobalt, ceramics, and some plastics; these tools are widely used in current production [107–110]. In this regard, UPM cutting tools are recommended to be manufactured using 3D printing, because numerous studies have demonstrated that 3D printing technologies used to manufacture a variety of cutting tools, such as carbide cutting tools, ceramic tools, milling cutters, and diamond blades, exhibit the required strength and unique properties for UPM [87,88]. Traxel and Bandyopadhyay [111] utilized 3D printing technology with directed energy deposition to develop carbide cutting tools with multiple wear-resistant layers. They found that adding diamond particles to the tungsten carbide–cobalt matrix improved tool sharpness and reduced chipping. Moreover, machining tests on aluminum materials reveal that carbide cutting tools manufactured via directed energy deposition with powder flow have a relatively rough surface. This feature reduces the cutting forces, friction, and surface temperature of the tools during scribing, and chipping size generated during scribing is only 312 μm, which is 35% lower than that of commercial tools, significantly improving machining performance. Wu et al. [103] investigated the VPP technique for the production of ceramic tools. Ceramic tools have higher hardness, wear resistance, and high-temperature resistance, and their comprehensive mechanical properties are superior to those of carbide tools, with 10 times the durability. These authors used VPP technology to manufacture ceramic tools with grooves and compared their dicing performance to commercial tools without grooves. Consequently, cutting and feed forces were reduced by 22.2% and 31.2%, respectively, compared with commercial tools, and the machined surface roughness was 0.46–0.75 μm.

In addition, the use of 3D printing technology enables the creation of unique structures, such as small groove structures, which further optimize tool performance. Skrzyniarz et al. [112] successfully produced milling cutters by using 1.2709 steel as a raw material with direct metal laser melting 3D printing technology. The condition of the cutting edges and their sharpness are essential factors in cutting operations; hence, the analysis of additively manufactured tools focuses on determining their dimensions and geometric accuracy, cutting edge radius, and surface quality. Therefore, these authors machined and ground milling cutters to produce sharp cutting edges with Rz and Ra of 4.6 and 23.5 μm, respectively, and could perform machining task accurately. He et al. [113] used fused decomposition modeling and sintering (FDMS) 3D printing technology to manufacture copper-based ultra-thin diamond blades and further investigated the effects of diamond parameters on the machining performance of the blades. The cutting tests revealed that diamond content and particle size exhibited an optimal proportion for high machining performance, and higher diamond content and finer diamond particles promoted agglomeration, which reduced the mechanical properties of the matrix, along with the pore and cavity structure generated by the FDMS process. Further dicing tests revealed that the FDMS fabricated copper-bonded diamond ultra-thin blades demonstrated high strength and were only 0.3 mm thick, allowing for the high-precision dicing of 0.088 and 0.075 mm blue wafers, which are complex and brittle materials. Su et al. [114] discovered the benefits of FDMS technology by analyzing the properties of cobalt-based diamond composites. They suggested that the FDMS process expanded the pores and cavities within the matrix, increasing the wear of the ultra-thin diamond blades and promoting diamond particle exposure. Consequently, dicing efficiency and quality were improved. Kong et al. [115] identified the chipping and porosity issues associated with the FDMS technique for producing ultra-thin diamond blades. Their proposed surface modifiers effectively improved the undesirable effects of poor filament characteristics and insufficient bonding, resulting in the production of ultra-thin diamond blades with a smooth surface and perfect flatness. Wu et al. [86] used 3D printing technology to design a gridded diamond drill bit, wherein the surface gridded working layer could obtain a higher specific pressure, improving its cutting efficiency during operation. Sandhu et al. [116] also used the FDM technique for tool production to obtain a new type of ABS tool and evaluate the surface characteristics of the machined expandable polystyrene. Increasing the feed rate and spindle speed could improve the dimensional accuracy and surface finish of the machined expandable . This finding was associated with cutting mechanisms, including microsphere dislocations and brittle fracture. Considering material properties, additional research is necessary to improve tool hardness and wear resistance by using ceramic or metal reinforcements to cut more rigid materials. Figure 2 presents some examples of cutting tools fabricated using 3D printing technology.

The aforementioned studies have demonstrated that the current 3D printing technologies for various materials, including metals, ceramics, plastics, and other materials, are mature and capable of fabricating many cutting tools for precision machining. In light of evidence from the literature of successful machining with high surface quality and machining performance of 3D-printed cutting tools, 3D-printed cutting tools are anticipated to be used in UPM with sufficient market development potential and benefits. Diamond, ceramic, and carbide tools are potential UPM cutting tools that can be manufactured via 3D printing.

3.2 UPM of 3D-printed components for real-world applications

The UPM of 3D-printed components can be crucial for preparing them in practical applications. Although 3D printing is a revolutionary technology, it frequently produces components that lack the required surface quality, dimensional accuracy, or proper mechanical properties for practical use. These issues can be resolved by UPM, and UPM enhances the functionality and surface quality of 3D-printed components. 3D printing techniques can be integrated with UPM to leverage machining advantages on final products.

UPM employs specialized cutting tools, particularly single-point diamond tools, to remove small quantities of material from the surface of a product. This machining approach can attain an exceptionally high level of precision, with tolerance as low as a few microns. The resulting surfaces exhibit tighter tolerance and improved mechanical qualities. Zhang et al. [118] emphasized that compared with other machining methods, such as chemical and physical, UPM has undergone longer development cycles and more machining experiences, providing greater versatility and certainty in the machining of complex surfaces exposed to a variety of engineering materials. The combination of this proposed strategy of virtual spindle tool servo and spiral toolpaths allows the form accuracy of the machined surface to be excellent, with prototype molds and replicas having a high degree of consistency and shape accuracy with a shallow surface roughness. However, UPM invariably results in issues, such as periodic plastic deformation of the tool surface, machining marks, and defects, which can gradually reduce machining accuracy. Furthermore, the debris and heat generated by the mechanical cutting method exacerbate this effect [119,120]. Xu et al. [121] also concluded that relying solely on machining for cutting makes meeting accuracy requirements difficult. Therefore, 3D printing combined with UPM can improve the imperfect machining results of each technology.

3.2.1 Mold inserts

3D-printed mold inserts present a cost-effective and efficient approach for complex shapes and personalized mold inserts. A mold insert is used to produce cavities or voids in a mold, which are filled with a substance, such as plastic, to form the final product. The advantages of 3D-printed mold inserts include their capacity to generate complicated shapes with fair precision and accuracy, their low cost, and short turnaround time. However, certain limits must be considered, such as the materials that may be utilized for 3D printing and the durability of the mold

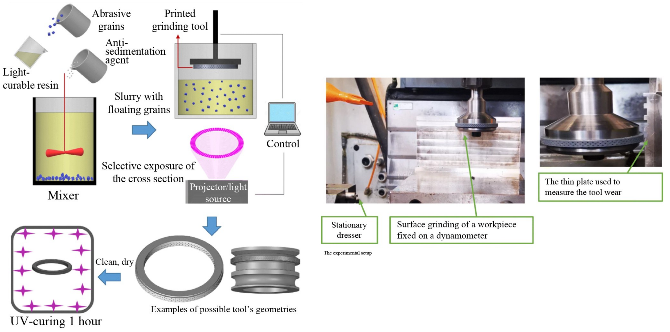
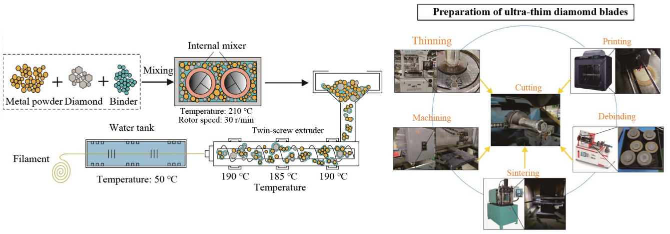
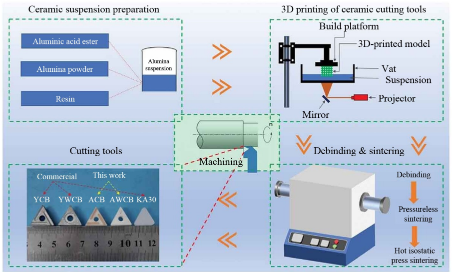
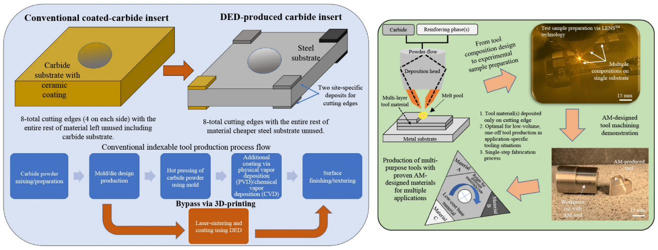
Literature source	Application dimension	Application mechanism procedure	Results
Ai et al., 2022 [109]	Resin bonded SiC grinding wheels manufactured by digital light technology		The surface roughness (Ra) of the ground aluminum sample was in the range between 1 and 2.5 µm, whereas it was approximately 0.2 µm for the hardened steel specimen.
He et al., 2023 [117]	Ultra-thin diamond blade manufactured by FDMS		FDMS diamond blades can improve the machining performance of processed materials, the machined surface quality, and the exposure of diamond particles on the blades.
Wu et al., 2023 [103]	Vat photopolymerization-based 3D printing Al_2O_3 ceramic tool		The relative density, Vickers hardness, bending strength, and fracture toughness of the manufactured cutting tools were 99.34%, 18.3 GPa, 513 MPa, and 3.5 MPa·m$^{1/2}$, respectively.
Traxel and Bandyopadhyay, 2021 [111]	Diamond-reinforced cutting tools using laser-based additive manufacturing		The tool machined aluminium and titanium specimens with a 35% and 64% lower built-up-edge, respectively, than those machined by conventional tools.

Fig. 2 Integration application of UPM and 3D printing for cutting tools. The listed case studies are from Refs. [103,109,111,117]. The images quoted above have been rearranged and reprinted with permission.

insert as its pore structures. Altaf et al. [122] emphasized the benefits of batch production, customization, and shape diversification, which can be achieved by preparing mold inserts by using 3D printing technology. Furthermore, the performance of 3D-printed mold inserts is gradually improving as technology and materials are further optimized. According to Boros et al. [123], 3D printing technology can better control complex structures and create bespoke properties, allowing the manufacture of complex structures with precisely controlled geometry. However, it inevitably increases the roughness of 3D-printed mold inserts. Gohn et al. [124] investigated the mechanical properties, dimensional accuracy, and surface finish of mold inserts prepared using 3D printing in various ways. The mechanical properties and surface finish of 3D-printed injection-molded abrasive contrast are considerably lower than those of traditional injection molds, with the tensile properties and modulus of elasticity being more than three times worse. Figure 3 illustrates the advantages of combining 3D printing technology with UPM technology in mold insert fabrication.

Despite the differences in structural properties caused by different printing materials, 3D printing technology is still plagued by dimensional tolerance, filling defects, and porosity, all of which significantly affect the surface finish and mechanical properties of printed components. Consequently, with the benefits of UPM, we propose that

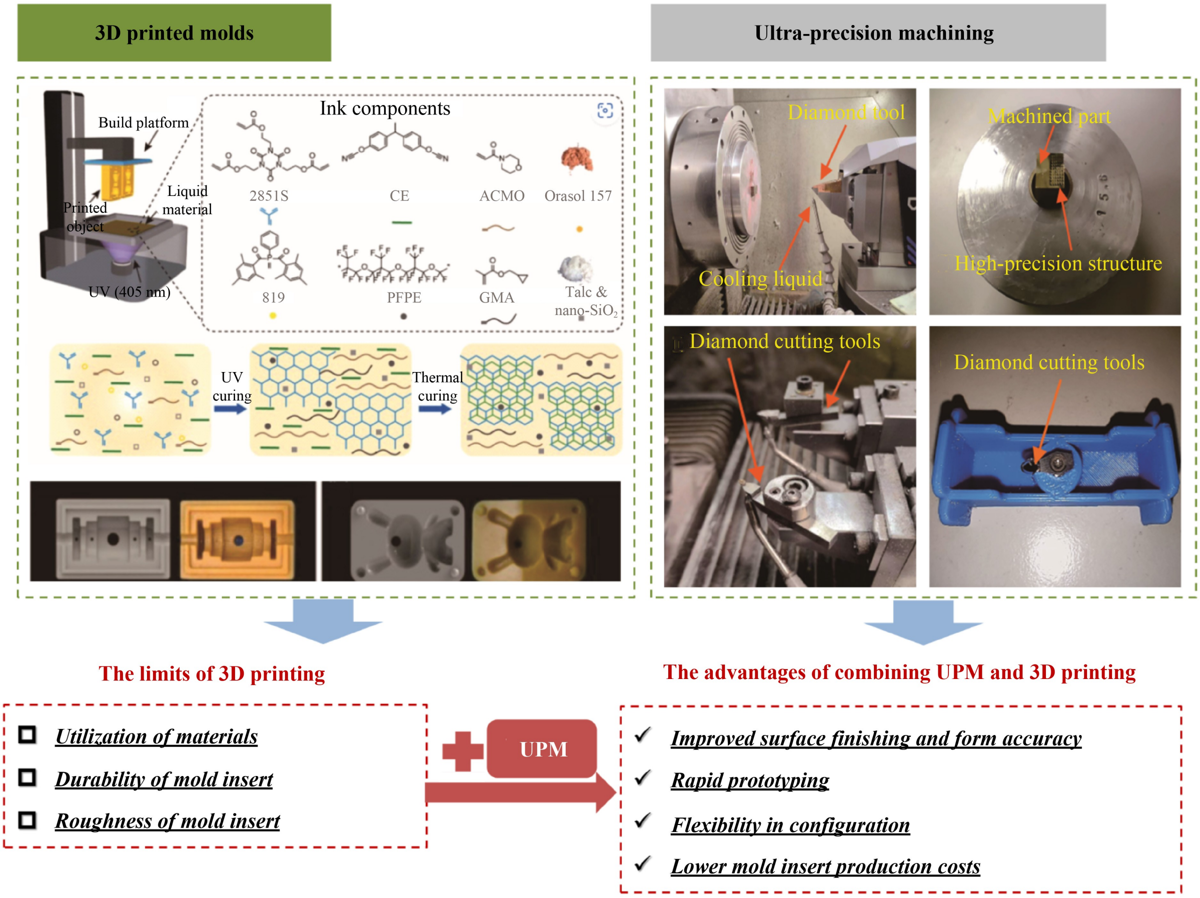


Fig. 3 Combining UPM and 3D printing for mold insert fabrication. The listed case studies are from Ref. [125]. The images quoted above have been rearranged and reprinted with permission.

3D printing can be used as a prototype mold insert and serve as a foundation for future research and development, with additional post-processing or finishing required for 3D-printed mold inserts to achieve appropriate surface uniformity, finish, and tolerance by UPM. By using the benefits of UPM on the surface quality and accuracy of machined components, the UPM of 3D-printed mold inserts can be a viable approach for overcoming the limitations of 3D printing and producing a smooth surface finish with less surface defect, allowing the generation of excellent-quality mold inserts and providing high-quality injection mold parts while extending mold life. In summary, the UPM of 3D-printed mold inserts exhibits the following advantages, synergizing the strengths of both technologies to enhance mold insert quality.

i. Improved surface finishing and form accuracy: UPM processes, such as diamond turning and micro-milling, produce incredibly tight tolerance and precise dimensions because these techniques employ diamond-cutting tools and machines that are capable of manufacturing highly accurate minimal features. This level of precision ensures that mold inserts fabricated via 3D printing accurately meet the requirements for the products of injection molding. It can also reduce friction and wear on mold inserts, extending mold life and lowering the risk of cracks or defects in the products of injection molding.

ii. Rapid prototyping: 3D printing can manufacture complicated geometries and designs quickly, and thus, it enables rapid prototyping of mold inserts. However, for high-quality mold inserts, the surface uniformity, form accuracy, and dimensional precision of 3D-printed mold inserts can only be sufficient occasionally. Post-processing the 3D-printed mold component with UPM can improve its accuracy and surface polish, resulting in a more precise and accurate mold. Fine details and features may be added to the mold insert by using UPM, resulting in a more accurate and precise mold insert with a short production time.

iii. Flexibility in configuration: 3D printing enables the manufacture of complicated geometries and patterns that will be difficult to produce with traditional mold insert fabrication techniques, such as rectangular arrays with perpendicular corners. However, 3D printing does not consistently deliver the requisite level of precision and surface polish. The accuracy and surface polish of a 3D-printed mold insert may be increased while maintaining its complexity by post-processing and enabling the production of highly customizable mold inserts that are fitted to individual part designs and manufacturing needs.

iv. Lower mold insert production costs: 3D printing is frequently less expensive than traditional mold insert fabrication technologies. Combining 3D printing and UPM can further reduce costs because UPM can be explicitly focused on the portions of the mold insert that require high accuracy and surface polish rather than machine for large or entire areas of the entire part. This condition reduces the amount of material that must be processed by UPM, lowering mold insert costs.

3.2.2 Optics

The most recent advancements in 3D printing technology enable highly controlled surface profiles with high resolution and high precision, opening up more possibilities for printing optical, refractive, and diffractive components and integrated optical systems, such as macroscale lenses, micro and nanoscale lenses, and multiscale lenses [126–128]. For example, Seniutinas et al. [129] used the femtosecond direct ink writing technique to create optical elements with sub-wavelength surface smoothness and sub-voxel accuracy, contributing to the accuracy of optical lenses. Sung et al. [130] created a suspended-drop inkjet printing process with a thermally assisted substrate to create optical lenses that are capable of achieving an imaging resolution of 1 μm when used for mobile phone photography, providing advantages that are not demonstrated by conventional optical lenses, despite the numerous applications of 3D printing technology in optical lens development and research. Despite the numerous applications of 3D printing technology in optical lens development and research, a trade-off exists between lens manufacturing speed and the required precision, particularly for optical lenses with a diameter greater than 1 mm. Furthermore, achieving the tight tolerance necessary for high-quality imaging is frequently challenging in developing optical lenses [131].

UPM is a machining technology that has revolutionized the optics industry by enabling the manufacture of high-quality optical components with close tolerance and precise dimensions. Traditional production procedures for optics, such as grinding and polishing, are time-consuming and limited in their capacity to manufacture complex shapes and features. UPM is an ideal method for optics fabrication and real-world case studies and applications. UPM is capable of producing microscopic features with excellent accuracy in optics. In addition, the machines used in UPM are designed to reduce vibrations, which can avoid distortion and inaccuracies in optics during fabrication. One of the most significant benefits of UPM in producing optics is the ability to attain tight tolerance and exact measurements, which are essential for manufacturing high-quality optical systems with exceptional image quality and clarity. In addition, UPM can generate various types of microstructures and micro-patterns on optical surfaces, such as lens arrays and dimple arrays, to act as functional surfaces [132] and ensure that optical components meet the required practical application standards. Overall, an integration of UPM and 3D printing in optics fabrication can address the challenges of each technology associated with tool wear, material properties, and microstructural patterns that arise during the fabrication process, as detailed in the subsequent discussion.

i. Reducing tool wear: 3D printing can create basic optics with raw shapes refined using UPM. By using 3D printing to create the initial shape in optics, the amount of materials that must be removed using UPM can be minimized, reducing the amount of tool wear.

ii. Expanding the choice of materials: 3D printing permits using a wide variety of materials, including polymers, metals, and ceramics that compensate for the short cutting distance of these materials in UPM. By using 3D printing to create the initial shape in optics, using an optimal material for the final optical properties is feasible. The component may be further processed using UPM to achieve the requisite precision and surface finish.

iii. Increasing the flexibility of internal structures: 3D printing can create structures with internal features or channels in optics that will be challenging to produce using UPM alone, as shown in Fig. 4.

3.2.3 Machineries

Numerous studies have demonstrated that using 3D printing technology in developing and modifying machines can significantly reduce production time by simultaneously performing AM and machining. As shown in Fig. 5, modularization of large machineries has occurred, wherein the module is manufactured with 3D printing technology, completing conceptual and practical innovations. For example, Lin et al. [137] combined the design concept of FDM 3D printing with a CNC milling machine to form an integrated hybrid machining device that can improve existing machining methods and capitalize on integrated design. By combining the design of the Prusa i3 as the original 3D printer and the VMC30 CNC machine center, the designed machine was able to operate smoothly. From the results of the Prusa-printed products, this combination of design concepts was effectively put into practice with a surface roughness of 96.723 μm, a surface roughness difference of 2.5%, and a tolerance of 0.5% after machining on the integrated machine. The realization of this concept breaks through the limitations of existing products and effectively broadens applications in the field of UPM. Furthermore, Durna et al. [138] considered laser engraving with SLS. The high temperature of laser was used to fuse and strip

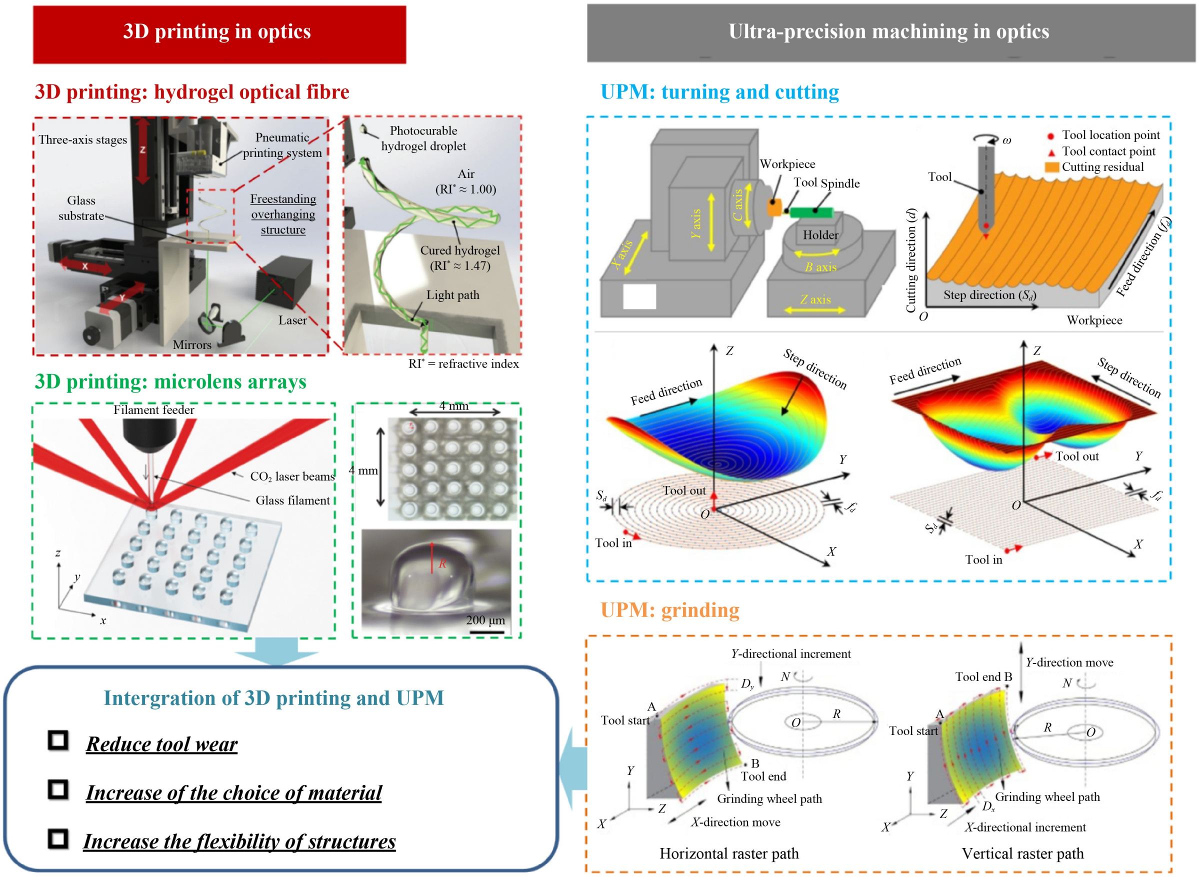


Fig. 4 Combining UPM and 3D printing for optics. The listed case studies are from Refs. [133–136]. The images quoted above have been rearranged and reprinted with permission.

the material, and the power of laser was varied to achieve high-precision cutting and etching of surface patterns. Using multiple angles of the same equipment significantly reduced the number of steps in product production. With knowledge on the relevant properties of the material to be processed, realizing this idea is possible by changing the parameters of the laser or adding other auxiliary materials as appropriate. Kostakis and Papachristou [139] presented a case study of a LEGO 3D-printed milling machine based on RepRap, where numerous LEGO parts, such as milling drills and support frames, were printed via FDM 3D printing technology and assembled into a milling machine. This case illustrates how breaking down significant equipment concepts and taking advantage of 3D printing technology to replicate fragmented units can catalyze the replication and production of numerous pieces of equipment, including machining milling machines, to enable further innovations.

Despite the relative maturity of current developments in 3D printing technology, more integrations with subtractive manufacturing techniques are necessary for UPM machineries, the combination of which is currently more experimental and requires more investment to realize the vision. Apart from 3D-printed components for machineries, they exhibit the potential and advantage to be used as other essential components in UPM, such as tooling, which can lead to several applications that break free from traditional UPM.

3.2.4 Microelectronic devices

As a third-generation semiconductor material, single-crystal silicon exhibits excellent electrical and chemical properties, including a broadband energy gap; it is widely used in high-temperature, high-pressure, high-power density, and radiation-resistant integrated electronic and optoelectronic devices [140]. This material is considered to have a high breakdown electric field and adequate chemical stability [132]. Moreover, it is an essential infrared optical material used as a substrate material to manufacture micro-components for electric and mechanical applications [141]. Monocrystalline silicon wafers are substrates that are widely used in producing microelectronic devices, such as ICs [142]. However, before forming wafer dimensions that range from a few hundred microns to tens of microns, a single crystal silicon (SCS) ingot must undergo several machining

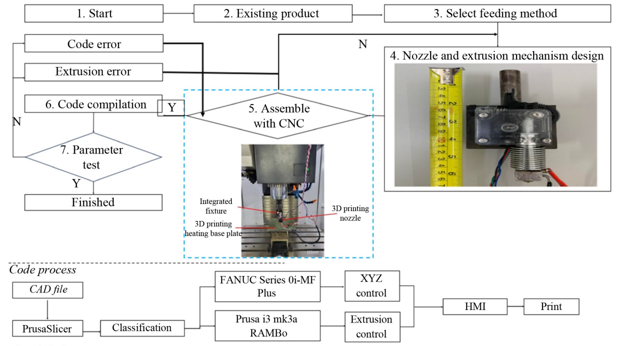
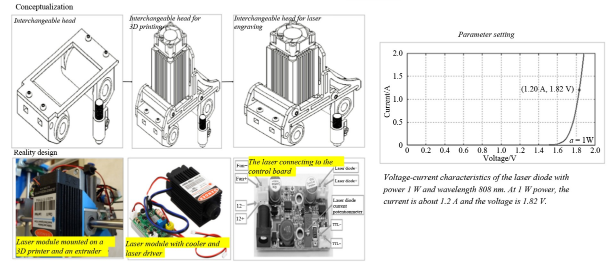
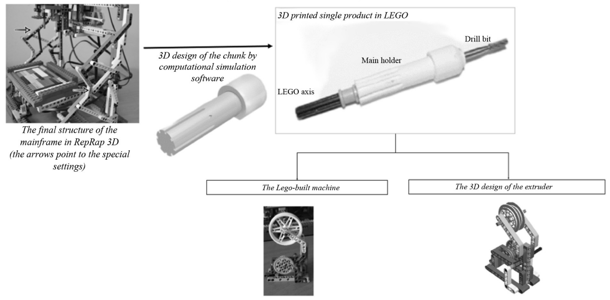
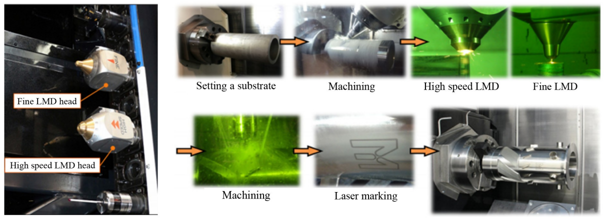
Literature source	Application dimension	Application mechanism procedure	Results
Lin et al., 2023 [137]	Integrated hybrid machining device through FDM-3D Printing		The surface roughness of the 20 mm × 20 mm × 20 mm cubical produced by the integrated machine tool was measured at 96.723 µm. The machining tolerance for this process is specified as 0.5%.
Durna et al., 2020 [138]	Laser engraving with SLS and SLM		The design optimally utilizes the machining space while minimizing the number of machining procedures.
Kostakis and Papachristou, 2014 [139]	LEGO 3D-printed milling machine based on RepRap		The technology modularizes the hardware components and lends itself to the development and replication of new technologies.
Yamazaki et al., 2016 [66]	Develop-ment of a hybrid multi-tasking machine tool		Sample: stainless steel alloy steel shaft; cost for multi-technology: $2500; cost for ordinary technical machining: $9000.

Fig. 5 Integration application of UPM and 3D printing for machineries. The listed case studies are from Refs. [66,137–139]. The images quoted above have been rearranged and reprinted with permission.

procedures to ensure good surface quality, including slicing, lapping, grinding for surface preparation, edge profiling, and polishing [141,143].

To meet the stringent flatness and nano-topography criteria, silicon wafers must be exceptionally flat and smooth. The requirements for these metrics become increasingly stringent as the size of the device's features shrinks over time [144,145]. Surfaces should possess a smooth and delicate finish, with a surface roughness (Ra) of 10 nm or less and minimal subsurface damage. The finished product should have crack-free mirror surfaces and a micro-roughness of less than 1.8 [146]. Polishing and lapping are the conventional methods for producing single-crystal silicon [147]; however, these methods can significantly improve process efficiency while producing high surface integrity [143,144]. Although monocrystalline silicon is considered brittle and challenging to process [141,144,147], ultra-precision diamond grinding is widely used in fabricating thin silicon wafers as substrate materials and the back thinning of fully processed wafers due to its low damage, high precision, and efficiency [142,148]. However, several challenges are addressed when utilizing ultra-precision diamond grinding for silicon wafer fabrication. Subsurface cracks, approximately half the size of diamond grits used in diamond grinding, can develop on silicon wafers [146,148]. In addition, surface pitting and dislocations with thicknesses in the sub-micrometer range are produced. Each grit on the grinding wheel creates a concentrated stress point perpendicular to the surface, leading to crack formation. Median crack formation is typically associated with material strength deterioration, while lateral crack formation is associated with material removal activities [146]. Brittle fracture is a common issue in the ultra-precision grinding (UPG) of silicon wafers [143]. Despite being able to cut nonferrous metals, such as aluminum and copper, for hundreds of kilometers, diamond tools quickly deteriorate and wear out when used in the precision cutting of single-crystal silicon [141,149]. The interaction between the tool and the workpiece plays a crucial role in generating plastic flow and preventing fracture during the grinding process. Excessive tool wear not only significantly increases machining costs but also compromises the quality of the final product, particularly when grinding large components. Therefore, the understanding of diamond tool performance in silicon machining must be improved to achieve cost savings in the production of SCS wafers [141,149].

Nowadays, 3D printing has applications in the electronics industry for creating free-form micro-components with high resolution and enhanced functionality [150]. This AM technique offers several advantages, including design freedom, the ability to generate planar and 3D patterns, fast and simple manufacturing, energy conservation, and environmental friendliness [151,152]. It enables the production of complex and arbitrary 3D structures, providing a high degree of freedom in electronic device design. The demand for microscale electronic components with sub-micrometer dimensions has increased due to the development of miniature technologies [153]. 3D printing has facilitated innovations in miniature manufacturing by allowing the production of micro- and nanoscale components with precision, accuracy, and control. In addition, it offers the advantage of high surface area-to-volume ratios, improving the physio-mechanical properties of microelectronics [71]. The simplicity, customization capabilities, and improved electrical performance offered by 3D printing make it highly suitable for microelectronic device fabrication [152]. Various multifunctional electronics, including sensors, circuits, embedded electronics, and structural electronics, can be created using this technique. For example, high-stretchable, soft-strain, and pressure sensors are types of sensors that have been successfully developed. Furthermore, 3D printing allows for the production of micro electrodes and other mini components with customized geometry and shape, reducing manufacturing costs, improving performance, and increasing production speed [152]. Micro supercapacitors, manufactured using 3D printing, have demonstrated higher areal capacitance and storage modulus.

Brittle fracture is also common during the UPG of silicon [143]. Moreover, the phenomenon of tool–workpiece interaction is critical for generating plastic flow and limiting fracture during the UPG of silicon crystals. Excessive tool wear escalates machining costs and compromises product quality, producing more challenges when grinding larger components and leading to significant cost savings associated with producing single-crystal silicon wafers [141,149]. AM and 3D printing offer significant potential for the one-step fabrication of microfluidic devices. However, producing stand-alone, nonmodular microfluidic devices with intricate embedded microchannel designs by using 3D printing is a challenge [150]. Several factors have hindered the widespread adoption of 3D printing in fabricating microfluidic devices [154,155], including constraints on achieving complex designs at the microscale, the requirement for a broader selection of transparent materials, limitations in the resolution of printing systems, the need for highly smooth surface finishes, and difficulties in precisely fabricating hollow and void sections with a high surface area-to-volume ratio. To overcome these obstacles and enable the application of 3D printing in biology and medicine, a hybrid manufacturing technique that combines 3D printing with laser micromachining lamination has been developed. This novel approach incorporates critical features in advanced microfluidic system architecture, such as increased design complexity, improved control over microflow in multiple directions, transverse multilayer flows, precise integrations of flow distribution, and enhanced transparency for high-resolution imaging and analysis. By combining the benefits of 3D printing and lamination, the hybrid manufacturing method eliminates the need for costly and time-consuming clean room fabrication while overcoming the design limitations of the lamination technique. This novel approach enables the fabrication of complex and custom microfluidic devices in three dimensions that incorporate transverse multilayer flow [156].

Despite the promising opportunities presented by 3D printing for the effective production and integration of various microelectronic components, this technology is still in its early stages and requires improvement. In microelectronics, effort should be focused on developing printable inks with the necessary properties. Electrically conductive inks pose a problem due to the porosity of parts, which can lead to short circuits. Specific issues are also associated with semiconductors, such as silicon, which are typically prepared as nanoparticles and mixed with other liquids to achieve the desired viscosity and printing properties. Subsequently, the annealing process removes the liquid, potentially affecting the properties of the printed components. Another major issue associated with the 3D printing of silicon microelectronics is the presence of grain boundaries and voids in the material structure. Obtaining a single-crystal structure that is free of these defects is a complicated process, and most high-performance devices require magnificent single-crystal structures. Furthermore, 2D microstructures, such as transistors, are built on 2D structures made of thin films. 3D printing for these micro-components has yet to be proven useful [157]. Energy conversion efficiency should be improved, along with the sensitivity of microsensors. Moreover, the nontoxic and biodegradable compatibility of various components must still be improved [152]. In the past 10 years, a novel approach known as hybrid manufacturing has emerged, with the goal of capitalizing on the benefits of various manufacturing techniques while addressing their individual shortcomings [158]. Hybrid AM was developed to capitalize on the advantages of AM in the production of a variety of materials. In the majority of hybrid AM processes, AM is combined with surface enhancement techniques as post-processing. These additional processes are intended to improve the surface characteristics, microstructure, metrological accuracy, and physical properties of the workpiece [158,159]. Despite significant advances in AM, the widespread application of AM components is still limited by a number of factors. These factors include the porous surface morphology, metallurgical defects, insufficient surface roughness, and dimension errors of the workpiece [160]. To overcome the limitations associated with surface accuracy and geometric tolerance, post-machining operations are essential, particularly for applications that are critical and precise in the fields of electronics and microelectronics [159,161,162].

A micro-electromechanical system (MEMS) combines microelectronic circuits with miniature mechanical structures to create extremely compact functional systems for sensing or actuation. The fabrication of MEMS microstructures necessitates a variety of well-established, material-specific techniques. For example, wet or dry etching is commonly used to micromachine silicon and glass, while injection molding, hot embossing, and soft lithography are used to create polymer microstructures [163–165]. For low-temperature co-fired ceramic substrates, the cutting and co-firing processes are utilized. Regardless of the employed materials and techniques, the production of MEMS devices is a multistep process that involves several technological aspects, such as photolithography, etching, deposition, bonding, and assembly [166]. A natural tendency to combine MEMS technology and 3D printing techniques exists. This convergence is advantageous for the low-cost, rapid, and high-volume fabrication of fully functional MEMS devices based solely on computer designs and a printer [167].

Emerging as a promising method for manufacturing microfluidic devices, 3D printing offers significant advantages over traditional techniques, such as mask-based photolithography. The key advantages of utilizing 3D printers in the production of microfluidic devices include cost-effectiveness, the ability to generate multiple thicknesses, the creation of complex 3D architectures, streamlined design processes, and the absence of cleanroom requirements [168,169]. To address surface-related issues with polydimethylsiloxane (PDMS), the surface of the 3D-printed template must be coated prior to PDMS casting. This coating layer acts as a barrier, allowing for proper PDMS polymerization on the surface of the mold and facilitating the removal of the PDMS layer after curing. The presence of residual monomers and catalysts on the surface of the printed mold can hinder curing or produce PDMS layers that are not peelable [170,171]. Obtaining the high resolution required for a variety of microfluidic applications is a further obstacle when manufacturing microfluidic devices by using 3D printers. The mechanical control of the printer and the properties of the printing materials affect resolution. Microstereolithography (SL) and projection SL (PSL) techniques are frequently preferred due to their ability to produce smooth surfaces at a reasonable cost [172,173]. However, high-resolution printing frequently has size restrictions, posing an additional challenge in the field. Using a laboratory-made PSL 3D printer to fabricate specific mold components with microstructure features to fabricate other mold components, such as the main chamber and microchannels, some researchers have developed an alternative method that helps overcome the resolution limitations of 3D printing while retaining the benefits of both techniques [174].

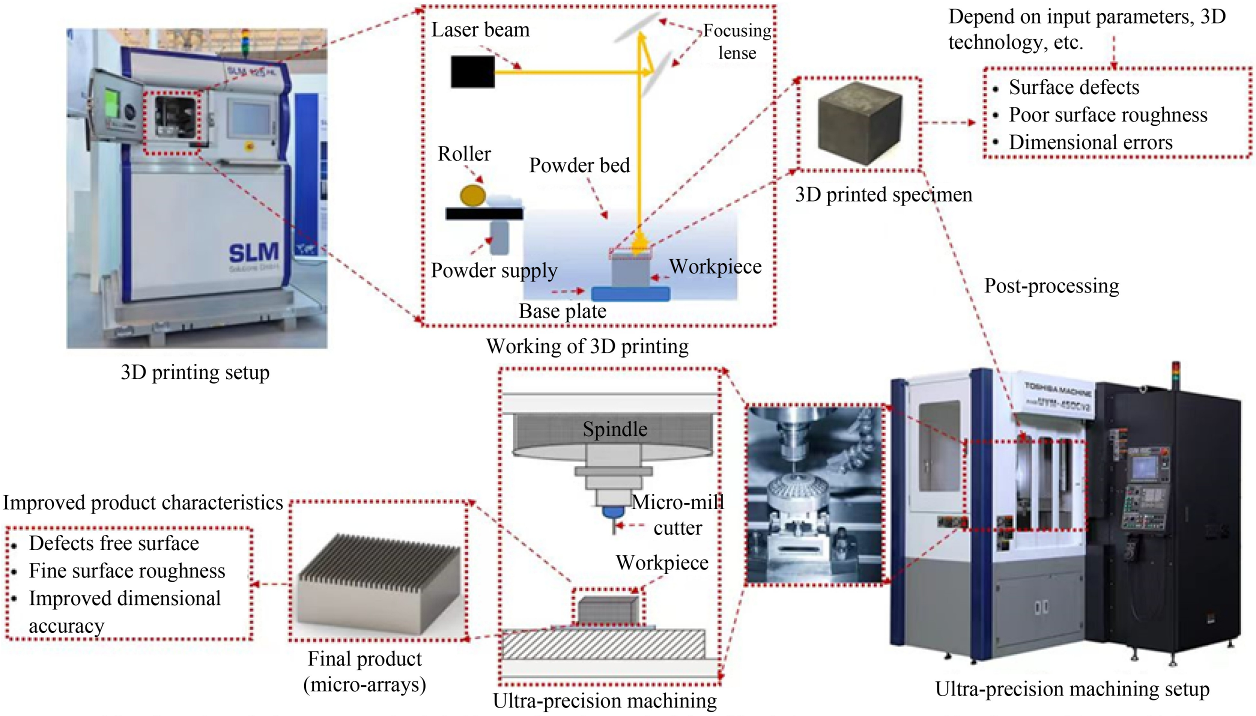
3.3 Post-machining of 3D-printed components by UPM

Significant resources are dedicated to developing and applying AM due to its research value and potential applications in aerospace and biomedicine. However, some critical issues, such as unruly surface topography as light changes, high surface roughness, inadequate dimensional accuracy, and the unfulfilling microstructure and mechanical properties of printed components, hinder the potential for using AM components in engineering and biomedicine fields. To address these issues, Oyelola et al. [175] suggested that 3D-fabricated components require additional post-processing. Investigating the post-processing of 3D-printed components in response to the rigorous surface quality and geometric accuracy specifications imposed by the precision requirements for advanced products is critical. UPM refers to the attainable level of excellent form accuracy and surface roughness below 10 nm. The resolution and reproducibility of the machines are less than 10 nm; therefore, the unsatisfactory surface quality of 3D-printed surfaces can be solved by UPM post-machining.

Sun et al. [176] introduced an improved UPM approach for 3D-printed zirconia ceramics, which increased the finishing efficiency of the developed shear thickening finishing media by over 24% compared with the conventional method. This previous study demonstrated the capability of UPM in producing ultra-precise finishing of 3D-printed zirconia ceramics with minimal flaws and distortions. According to Ni et al. [177], extensive research is being conducted on the effect of additively manufactured Ti-6Al-4V alloys on machining performance in UPM. The machining findings revealed that the anisotropic mechanical characteristics and microstructures of Ti-6Al-4V alloys are the primary causes of anisotropic machining performance in cutting forces and surface roughness. By contrast, surface roughness improved significantly along a particular laser scanning direction on the samples when a certain cutting depth was adopted. Behroodi et al. [174] employed a microwell section mold manufactured using a laboratory-made PSL printer. Then, micro-milling was used to create other mold elements, such as the main chamber and micro-channels. Integrating 3D printing with the CNC micro-milling process and micro-milling and 3D printing methodology dramatically simplifies the manufacturing process of large-scale microfluidic devices and quick prototyping with high-resolution microstructures. Varghese and Mujumdar [178] studied the influence of micromachining on the surface integrity and cutting forces of 3D-printed Ti-6Al-4V alloy. The researchers discovered that the mean cutting force was lowest while machining porous materials, such as 3D-printed components, increased as cut depth increased. These studies demonstrate ongoing research effort to enhance UPM for 3D-printed components.

In the field of biomedicine, the material properties, structural accuracy, molding effects, and biological characteristics of 3D printing must be carefully considered and analyzed. Aldesoki et al. [179] used SLA 3D printing technology and precision machining to create ceramic root implants. Their findings revealed that milled crowns exhibited greater accuracy, whereas 3D-printed crowns showed some biocompatibility. A judicious combination of the two technologies exhibits the potential to enhance the promise of 3D-printed crowns. With regard to micro- and nanostructures in biology, 3D printing has excellent potential. It cannot only change the physical macro-elastic properties and improve the implantation of heart valves in simulated aortic tissues, but it can also create intricate multilayered micro- and nanocomposite structures that influence the biodegradation time of human implants [74, 180]. For example, Kim et al. [75] found that the directional consistency of fibers influenced contact guidance strength, which, in turn, affected cell attachment and growth direction. These groundbreaking biomedical applications not only require advancements in 3D printing technologies and processes, but also the synergistic integration of post-processing techniques. UPM and 3D printing technology are critical for realizing the clinical potential of these combined technologies [181].

Overall, the post-machining of UPM on 3D-printed components improves surface finishing, provides higher



Manufacturing of micro-arrays using hybrid manufacturing method, i.e., 30 printing post processed by ultra-precision machining

Fig. 6 Proposed hybrid UPM and 3D printing for microstructures fabrication.

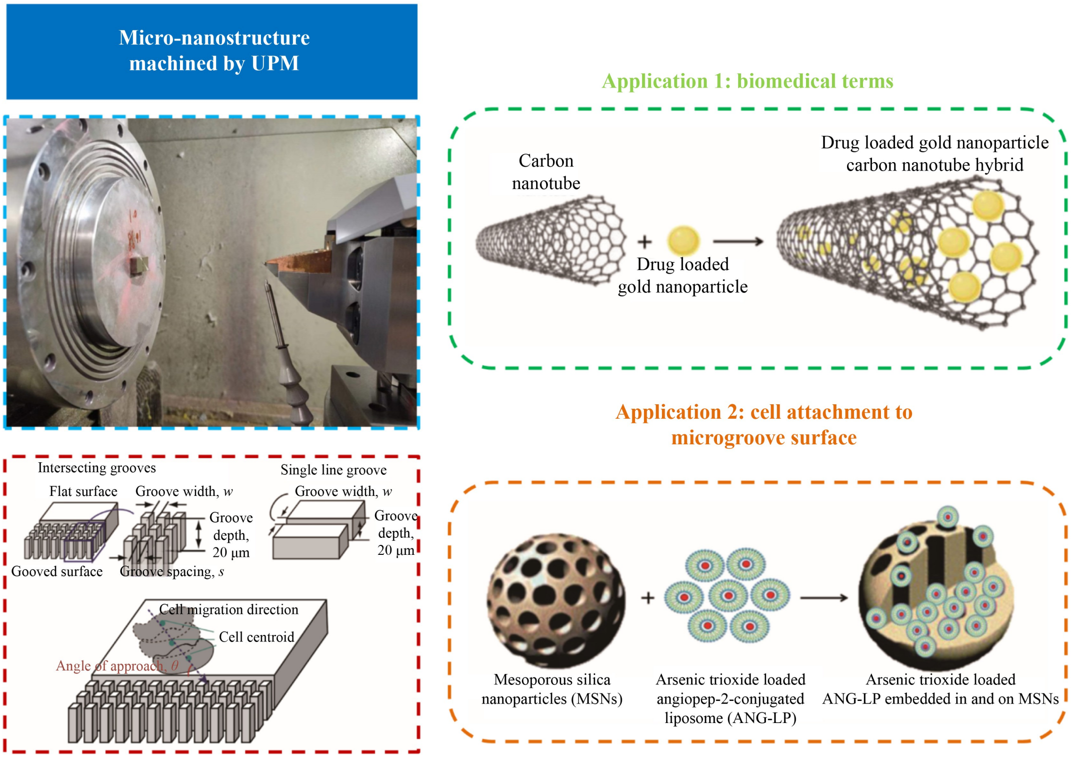


Fig. 7 Potential micro- or nanostructures for biomedical applications. The listed case studies are from Refs. [182,183]. The images quoted above have been rearranged and reprinted with permission.

tolerance, and enhances the material properties of the components. Rough surface finishes on 3D-printed components may degrade their performance, while UPM may improve the surface quality of 3D-printed components by reducing roughness and generating a smooth surface finish. In addition, post-machining via UPM may produce tighter tolerance and increase the accuracy of component dimensions, resulting in better fit and more excellent functioning of 3D-printed components. Meanwhile, the layer-by-layer manufacturing of 3D-printed components can result in anisotropic material characteristics, affecting their strength and endurance. By investigating anisotropic layers and providing UPM with the desired cutting directions, UPM can enhance the material characteristics of 3D-printed components. Figure 6 shows the proposed hybrid 3D printing and UPM for fabricating microstructures. Figure 7 illustrates the application of micro- or nanostructures in biomedical fields.

4 Summary and future perspectives

As previously stated, the benefits of integrating UPM and 3D printing technology have been established. Industries that require high surface quality and frequently utilize UPM and 3D printing components can significantly benefit from this integration. With this logic, we propose prospects for integrating the two advanced technologies in the tool, mold, machinery, microelectronics, and post-finishing of 3D-printed components.

Combining UPM and 3D printing can revolutionize the tool industry by enhancing tool performance and customization. Complex tool components with intricate geometries can be quickly produced by utilizing 3D printing. In addition, UPM can be employed to refine the surface finish, dimensional accuracy, and mechanical properties of these 3D-printed tools. Moreover, UPM allows for generating micro-patterns on 3D-printed tools, which can serve specific purposes and result in the development of cutting tools with improved performance and longevity. This process leads to the development of cutting tools with improved machining performance and fast speed, which are suitable for tailor-made cutting tools customized in accordance with a customer's specific needs by resolving the long production time. Some commercial companies, such as Mantle3D (US) and All3DP (Germany), are beginning to use hybrid AM and subtractive manufacturing to automate and accelerate component production. This trend will spread to this technology as a result of the anticipated rapid development of ultra-precision and micro-tooling.

Furthermore, the combination of UPM and 3D printing exhibits the potential to open up new opportunities for the mold and biomedical industries. For example, 3D printing can be used to fabricate complex mold inserts with intricate geometries or the scarifying 3D printing mold insert part and further texturing via UPM to improve surface finish, dimensional accuracy, and material properties. Consequently, molds with improved functionality and a wide molding shape for components can be created. Mold inserts with micro- and nanoscale features are another potential application of the integration of UPM and 3D printing in the mold industry. Molds with complex geometries and shapes can be produced using 3D printing, while UPM can improve the surface finish and dimensional accuracy of the micro- and nanoscale features. This condition can result in the creation of molds with improved surface integrity and resolve the long production time for mold inserts. Similarly, clinical demand in the biomedical field for implants or models of human organs with complex geometries and features at the micro- and nanoscales is significant. These applications include flexible soft-bodied robots for drug delivery, models of teeth and roots made from bio-glasses and ceramics, and various metal joints, stents, and other implants. Leveraging 3D printing technology and UPM can advance the research and development of new medical devices and products. However, addressing ethical, safety, and stability considerations is crucial during this process [184]. Figure 8 summarizes the future perspectives of hybrid 3D printing and UPM proposed in this study.

In the future, the comprehensive application fields of UPM and 3D printing can be widely popularized in the tool, mold, and biomedical industries. In the tool industry, 3D printing can be used to improve performance and longevity by creating complex components and achieving custom cutting tools, respectively, and to resolve the long production time while enhancing machining performance. In the mold industry, improvement in functionality and surface integrity, the creation of wide molding shape for the components, and the resolution of the long production time are achieved through fabric complex or scaling mold insert with micro- and nanoscale features. In the biomedical industry, the development of medical implants that utilize enhanced cell culture, the monitoring of the heating process, and the enhancement of precise and controlled movements are achieved by creating complex and nano/microstructures medical implants and manufacturing medical devices with embedded sensors and actors. The implementation of these applications necessitates additional integration and technological innovation. Intelligent manufacturing and processing, which represent a new generation of high-value technology, are gradually displacing traditional manufacturing and processing technologies. These technologies are capable of autonomous learning and automatic detection, and they exhibit the potential to significantly improve industrial production and processing efficiency [185]. For example, in the Industry 4.0 era, the integration of AI and industrial manufacturing will improve predictive maintenance, quality control, and supply chain management, lowering operating costs and increasing productivity [186]. The combination of 3D printing technology and AI has already been demonstrated in 4D printing, where time dimension control, and intrinsic model training and learning, have resulted in improved print quality, accuracy, and efficiency [187,188]. Adaptive control and regulation systems in UPM technology have also improved in sensitivity and precision due to repeated and enhanced machine learning [186,189]. This condition improves high-precision machining efficiency while encouraging energy conservation and sustainable development. To summarize, future research will focus on improving the level and effectiveness of intelligent 3D

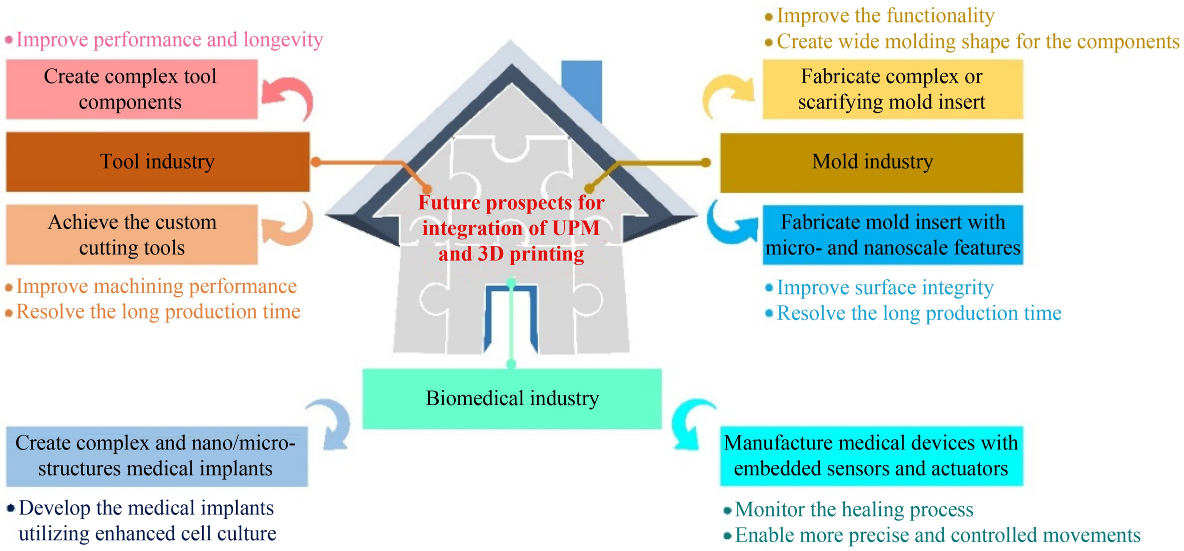


Fig. 8 Future perspectives of hybrid 3D printing and UPM.

printing technology and intelligent UPM technology. It will also add significant application value to additional fields.

5 Conclusions

AM, particularly 3D printing, has revolutionized the manufacturing industry by facilitating the cost-effective and efficient production of complex and delicate components. To obtain the required surface quality, accuracy, and mechanical properties, 3D-printed parts frequently necessitate integration with another machining technology. UPM is a prospective technology that enables nano-grade surface generation, potentially eliminating the disadvantages of 3D-printed components. This study offers a new perspective on the current state of UPM for 3D printing, opportunities, and future perspectives. In particular, the highlights of this study are as follows.

i. The advantages of combining UPM with 3D printing, and the opportunities for leveraging UPM on 3D printing or mutually supporting each other, are presented.

ii. The opportunities focus on cutting tools manufactured via 3D printing for UPM, the UPM of 3D-printed components for real-world applications, and the post-machining of 3D-printed components are demonstrated in detail, with examples and discussions of the advantages.

iii. From a future perspective, potential industries that will benefit from integrating the two advanced manufacturing technologies are discussed, including the tools, molds, and industries.

Nomenclature

Abbreviations

ABS	Acrylonitrile butadiene styrene
AI	Artificial intelligence
AM	Additive manufacturing
ANN	Artificial neural network
BJ	Binder jetting
CNC	Computer numerical control
DED	Direct energy deposition
DOC	Depth of cut
DLMF	Direct laser metal forming
DLMS	Direct laser metal sintering
EBM	Electron beam melting
FEM	Finite element modeling
FDM	Fused decomposition modeling
FIB	Focused ion beam
FIBID	Focused ion beam induced deposition
IC	Integrated circuit
LENS	Laser-engineered net shaping
LOM	Laminated object manufacturing
MEMS	Micro-electromechanical system
MD	Molecular dynamics
PBF	Powder bed fusion
PDMS	Polydimethylsiloxane
PLA	Polylactic acid
SCS	Single crystal silicon
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
SPDT	Single-point diamond turning
UPM	Ultra-precision machining
UPG	Ultra-precision grinding
UV	Ultraviolet
VPP	Vat photo-polymerization

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