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Introduction

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Ceramics are a class of inorganic, nonmetallic materials that are typically hard, brittle, and resistant to deformation and abrasion. They are one of the oldest and most diverse classes of materials known to humankind, ranging from traditional pottery to cutting-edge advanced ceramics [1]. Traditional ceramics, such as earthenware, stoneware, and porcelain, are crafted from natural materials like clay and are fired at high temperatures to create durable and aesthetically pleasing items for everyday use and art. Advanced ceramics, on the other hand, are a category of materials engineered for specific high-performance applications. Structural ceramics, such as oxide ceramics (e.g. alumina and zirconia) and non-oxide ceramics (e.g. silicon carbide and silicon nitride), are chosen for their exceptional mechanical properties, including high strength, hardness, and wear resistance, making them ideal for components in extreme environments like aerospace and automotive industries [2, 3]. Functional ceramics, which include piezoelectric and ferroelectric materials, are valued for their unique electrical properties [4]. These materials can convert mechanical stress into electrical signals, or vice versa, and are crucial in sensors, actuators, and electronic devices. Advanced ceramics also encompass bioceramics, used in medical implants due to their biocompatibility, and ceramic matrix composite (CMC) materials, which exploit the properties of composites for enhanced performance [5, 6]. These advanced ceramics are revolutionizing industries with their high performance and specialized functionalities. The categories of different ceramics are illustrated in Figure 1.1.

In the domain of advanced science and technology, ceramics play a crucial role in various applications due to their unique properties. This section will delve into the most important properties of ceramics, their typical processing and fabrication techniques, as well as the challenges and the need for additive manufacturing (AM) technologies.

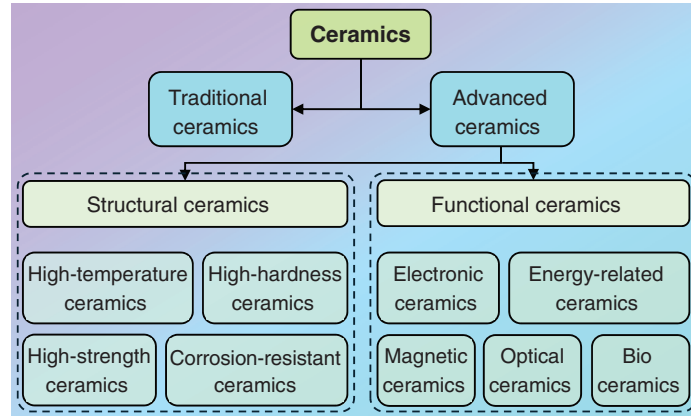


Figure 1.1 Categories of different ceramics, specifically of advanced ceramics.

1.1 Most Important Properties and Applications of Ceramics

Ceramics have been an integral part of human civilization for thousands of years, evolving from simple pottery to sophisticated materials used in advanced technologies. The unique properties of ceramics make them indispensable in various industries, from aerospace to medicine.

1.1.1 Most Important Properties of Ceramics

- **Chemical stability:** One of the most notable properties of ceramics is their chemical stability [7]. They are highly resistant to chemical attack and corrosion, which makes them suitable for applications in environments where metals would deteriorate. This resistance is particularly valuable in chemical processing plants, where ceramics can be used to line reactors and storage vessels, protecting them from corrosive substances [8].
- **Thermal stability:** Ceramics are known for their ability to withstand high temperatures without significant degradation [9]. This thermal stability is crucial in applications such as furnaces, kilns, and engine components, where materials must operate under extreme heat. For instance, ceramic tiles on spacecraft are designed to protect against the intense heat generated during re-entry into Earth's atmosphere [10].
- **Electrical insulation:** Most ceramics are excellent electrical insulators, a property that is vital in electronic devices and high-voltage applications [11]. Their insulating capabilities prevent the flow of electric current, making them ideal for use in insulators, capacitors, and other electronic components that require dielectric materials [12].
- **Mechanical strength:** Despite their brittleness, ceramics can exhibit high compressive strength, which makes them suitable for load-bearing applications [13].

This strength is leveraged in construction materials and in the manufacturing of components that must support heavy loads without significant deformation or fracture [14].

- **Hardness:** The hardness of ceramics makes them resistant to wear and abrasion, a characteristic that is beneficial in cutting tools and industrial machinery [15, 16]. Ceramic knives, for example, maintain their sharpness longer than their metal counterparts due to their hardness.
- **Optical properties:** Some ceramics possess unique optical properties, such as transparency, which is essential in applications like optical fibers and laser components [17]. The transparency of certain ceramics allows light to pass through with minimal scattering or absorption, making them ideal for fiber-optic communication systems [18].
- **Biocompatibility:** Certain types of ceramics are biocompatible, meaning they can be integrated with living tissue without causing adverse reactions [19]. This property makes them suitable for medical implants and prosthetics, such as hip and knee replacements, where the ceramic materials can mimic the physicochemical characteristics of bone [20, 21].

1.1.2 Main Applications of Ceramics in Advanced Science and Technology

The unique properties of ceramics – chemical stability, thermal stability, electrical insulation, mechanical strength, hardness, optical properties, and biocompatibility – make them a versatile and essential material in a wide range of applications. Figure 1.2 illustrates the main cutting-edge applications of advanced ceramics.

Structural ceramics are engineered to perform under high mechanical, thermal, and tribological stresses, as well as in corrosive environments and high temperatures [22]. They are used across a variety of domains and products due to their superior strength, thermal stability, and wear resistance. Here are some specific examples of applications and fields where structural ceramics are utilized. They are used in precision cutting tools to extend tool life, as well as in high-performance bearings and seals, and wear-resistant machine components, due to their high strength and high hardness. They are used in aerospace industry as part of gas turbines, nozzles, and heat exchangers due to their ability to resist high temperatures, mechanical stresses, corrosion, and chemical degradation under critical environments characterized by extreme conditions [23]. They can also be employed in automotive industry as high-temperature engine components, brake system elements, and exhaust systems to improve performance and durability [24]. Moreover, various laser components like pump chambers, feedthroughs, waveguides, and ion tubes are often made of porous ceramics, especially alumina [25]. Moreover, CMCs combine the high-temperature resistance of ceramics with the toughness of composite materials [26]. They have been developed for use in advanced aircraft engines and other high-stress environments. CMCs offer superior mechanical properties such as high strength, stiffness, and toughness, making them suitable for structural components in energy storage systems and lightweight, durable enclosures [27].



Figure 1.2 Advanced ceramics for cutting-edge applications.

Oxide ceramics, such as alumina (Al_2O_3), zirconia (ZrO_2), and silica (SiO_2), are known for their versatility, low cost, and relatively abundant resources. These ceramics are widely used as structural ceramics, such as in aerospace applications, for their high-temperature stability, hardness, and corrosion resistance. For instance, they are used in the ceramic cores for casting turbine blades for aircraft engines [28], as well as in heat-resistant tiles for spacecrafts [29]. Non-oxide ceramics, including carbides, nitrides, and borides, are characterized by higher temperature resistance, increased strength, and fracture toughness compared to oxide ceramics [30]. Silicon carbide (SiC) and silicon nitride (Si_3N_4) are used in structural applications requiring high thermal conductivity and mechanical strength, such as in aerospace, semiconductor equipment, energy and environmental protection, and nuclear power, as advanced structural components [31–38]. Non-oxide ceramics like tungsten carbide (WC) and boron carbide (B_4C) are utilized in superhard abrasives and cutting tools due to their extreme hardness [39, 40]. Furthermore, non-oxide ceramics are used in rocket nozzles and electrodes due to their ability to withstand high temperatures and chemically aggressive environments [41]. The above-mentioned applications highlight the versatility and importance of structural ceramics in modern manufacturing and engineering, where their unique properties provide solutions for demanding performance requirements.

Advanced ceramics often also possess certain required functional properties, alongside their structural features. For example, optical ceramics not only need excellent optical properties, high transparency in particular, but also require high

resistance to fracture and durability for long-term use. Bioceramics are used in wear surface applications such as femoral hip and acetabular structures, as well as in spinal applications and dental implants [42]. Besides structural features like load bearing and wear resistance, their biocompatibility also makes them preferred materials over metals, as they better mimic the properties of bone and are less likely to cause rejection by the body's immune system. Oxide structural and functional ceramics represented by alumina and zirconia are widely used in optical communication and semiconductors, electronic packaging substrates, sensors, medical devices, smart wear, electric vehicles, and other fields. For example, they are widely used as functional electronic ceramics in the electronics industry, particularly in multilayer ceramic capacitors (MLCCs) and resistors [43]. Semiconductor equipment such as photolithography machines, plasma etchers, ion implanters, heat treatment furnaces, and diffusion furnaces required for semiconductor wafer and chip manufacturing use a large number of high-purity alumina, aluminum nitride, yttrium oxide, silicon nitride, and silicon carbide ceramic parts (such as electrostatic and vacuum chucks, handling arms, wafer carriers, and etched rings) [44]. Aluminum nitride (AlN) with high thermal conductivity is not only widely used in electronic packaging substrates but is also now part of insulated-gate bipolar transistors (IGBTs) in electric vehicles and wind power generation systems [45]. Other functional ceramics include piezoelectric ceramics, which generate an electric charge in response to mechanical stress, making them invaluable in sensors, actuators, and energy harvesting devices [46–48]. Their ability to convert mechanical stress into electrical signals is crucial in various technological applications, from medical imaging to industrial automation. Energy-related ceramics are critical in advancing energy storage and conversion technologies, combining high efficiency, durability, and tailored electrical properties. In solid oxide fuel cells (SOFCs), ceramics like lanthanum strontium cobalt ferrite (LSCF) and yttria-stabilized zirconia (YSZ) enable high electronic and ionic conductivity [49], while transition metal oxide-based functional ceramics such as lithium iron phosphate (LiFePO_4) serve as the cathode materials in lithium-ion batteries [50]. Electromagnetic wave absorption has now become a demanding functional feature for ceramic composite components used in aerospace applications [51, 52].

Table 1.1 demonstrates the selected applications of ceramics in various domains and relevant properties required. Oxide ceramics are favored for their electrical and thermal insulation properties in electronics and aerospace, while non-oxide ceramics are chosen for their superior mechanical properties and high-temperature performance in cutting tools, electronics, and high-stress environments.

Ceramics have come a long way from their ancient origins to become a cornerstone in advanced science and technology. Their unique properties make them indispensable in a wide range of applications, from aerospace to medicine. As research continues to push the boundaries of what ceramics can do, their importance is only set to grow. The development of nanoceramics [53], self-healing ceramics [54], and ceramic-based quantum technologies [55] is just a few examples of how ceramics are shaping the future of technology. As we look to the future, ceramics will undoubtedly continue to play a vital role in the advancement of human knowledge and the development of new technologies.

Table 1.1 Applications of ceramics in various domains and relevant properties required.

Application field	Ceramic components used	Ceramic properties required	Typical relevant ceramics
Aerospace	- Heat shields - Heat exchangers - Turbine blades - Reflecting mirrors	- High-temperature resistance - High strength - Thermal stability - Low density	- Boron nitride - Carbo-silicon carbide - Silicon carbide - Titanium diboride
Electronics	- Capacitors - Resistors - Substrates - Sensors	- Dielectric properties - Thermal conductivity - Thermal stability - Electrical insulation	- Alumina - Barium titanate - Lead zirconate titanate
Biomedicine	- Artificial bone implants - Dental implants - Dental veneers	- Biocompatibility - Biodegradability - Porosities - Hardness - Aesthetics	- Silicon nitride - Alumina - Hydroxyapatite - Silicon nitride - Tricalcium phosphate - Zirconia
Energy	- Fuel cells - Batteries - Furnaces - Nuclear power	- High-temperature resistance - Corrosion resistance - Chemical stability - Mixed electron and ion conductivities	- Alumina - Zirconia - Lanthanum strontium cobalt ferrite - Lithium iron phosphate - Lithium orthosilicate - Ytria-stabilized zirconia
Automobile	- Automotive engines - Brake system elements - Bearings	- Heat resistance - Wear resistance - High strength - High hardness	- Alumina - Silicon carbide - Silicon nitride - Zirconia
Environmental protection	- Ceramic filters - Ceramic membranes - Catalytic converters	- High-temperature resistance - Corrosion resistance - Thermal stability - Porosities	- Alumina - Cordierite - Silicon carbide - Silicon nitride
Optics	- Lenses - Light guides - Optical windows - Beam splitters	- Transparency - High strength - Thermal stability	- Aluminum oxynitride - Yttrium aluminum garnet - Zirconium silicate
Others	- Jewelry - Commercial device casings	- Strength - Hardness - Surface finish - Chemical stability - Aesthetics	- Zirconia - Alumina - Cordierite

1.2 Typical Processing Routes and Manufacturing Techniques for Ceramics

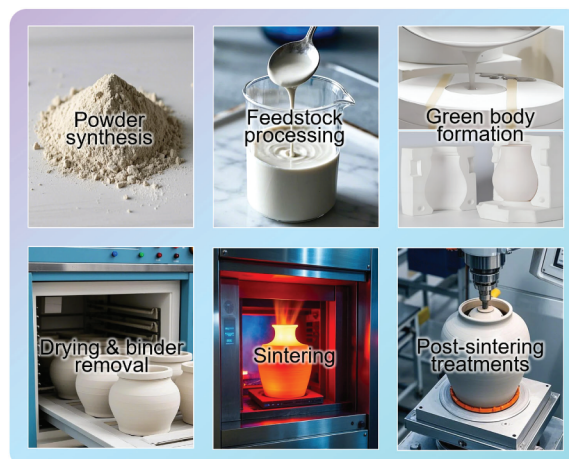
The processing routes and fabrication techniques for ceramics have undergone significant advancements since their traditional use as pottery and bricks, particularly with the development of advanced ceramics for specialized uses in industries such as aerospace, electronics, and biomedical.

1.2.1 Typical Processing Routes for the Fabrication of Ceramic Components

Advanced ceramics require sophisticated processing techniques due to their specialized applications and the need for high purity and precise control over microstructure. The typical processing route for the fabrication of ceramic components includes the following steps, as also illustrated in Figure 1.3:

- **Powder synthesis:** High-purity powders are synthesized through various chemical processes, such as precipitation from solution, sol-gel processes, or vapor-phase synthesis.
- **Feedstock processing:** The synthesized powders are then mixed with organic solvents and additives to form pastes or slurries that can be further processed.
- **Green body formation:** The processed powder is shaped to form a green body, which is the unsintered, pre-fired body of the desired ceramic part. This can involve techniques such as dry pressing (if no solvent is added), plastic forming, and casting.
- **Drying and binder removal:** The green body is dried, and any binders or organic additives are removed through a process called debinding, which can be carried out thermally or using chemical solvents.

Figure 1.3 Typical processing routes for the fabrication of ceramic components.



- **Sintering:** The green body is sintered at high temperatures to obtain the final dense and strong ceramic component. Sintering can be carried out through various methods, including conventional sintering, hot pressing, and spark plasma sintering (SPS).
- **Post-sintering treatments:** Depending on the application, the sintered ceramic may undergo additional treatments such as machining, glazing, or polishing to achieve the desired properties or appearance. Complicated post-processing such as polymer infiltration and pyrolysis may also be used for further densification and performance enhancement purposes.

1.2.2 General Manufacturing Techniques for Ceramics

The shaping and manufacturing techniques for ceramics have evolved to accommodate the diverse range of properties and applications expected from the components. Some of the key techniques include:

- **Forming:**
 - **Dry pressing:** A forming technique suitable for simple shapes, where dry or semi-dry powders are compacted in a die under high pressure to form the desired shape.
 - **Cold/hot isostatic pressing:** Techniques used for advanced ceramics where a flexible mold containing the ceramic powder is subjected to high pressure from all sides under high or low temperature simultaneously, resulting in a highly homogeneous, dense, and strong final product.
- **Molding:**
 - **Extrusion molding:** A continuous process where a viscous mixture of ceramic particles and binders is forced through a die to form a shape, which is then cut into pieces and dried.
 - **Injection molding:** Similarly to polymer processing, a mixture of ceramic powder, plasticizer, and thermoplastic polymer is injected into a mold under high pressure and then sintered after the polymer is removed. This method can produce relatively complex shapes with tight tolerances.
 - **Rolling molding:** A process that shapes ceramics by passing them between rollers.
- **Casting:**
 - **Slip casting:** A traditional method where a slurry of ceramic powder is cast into a plaster mold. The water is drawn out by capillary action, leaving a layer of ceramic particles that form the shape of the mold.
 - **Tape casting:** Used for producing thin, flat ceramic sheets, this method involves spreading a slurry of ceramic powder, binders, and plasticizers onto a carrier film, then drying it to form a tape.
 - **Gel casting:** A forming technique where a ceramic slurry is mixed with a monomer, poured into a mold, and then polymerized to form a green body.

As mentioned earlier, sintering at high temperature is needed after the binder removal process, where the ceramic body is further heated to a temperature

below the melting point of the ceramic material to allow particle bonding and densification, together with coarsening. The densification can be further improved by high-pressure sintering to achieve better mechanical properties of the final ceramic parts. There are also precision machining processes involved for further refinement of the shaped/manufactured ceramic parts before and after sintering. They include abrasive grinding and polishing, as well as tooling and cutting. Some other methods such as chemical and electrical polishing might also be used to achieve a smooth surface finish and tight tolerances. They can also be used to remove any surface defects introduced during sintering.

1.3 Challenges and the Need for Additive Manufacturing

The above-mentioned shaping, forming and manufacturing methods have undergone significant advancements in the ceramic industry in the past few decades. However, these methods face significant challenges. They often necessitate the use of molds, which can be demanding both in terms of process time and economic costs, and limit the production of highly complex or customized parts. Additionally, the inherent brittleness and hardness of ceramic materials present challenges in machining, also leading to difficulties in achieving intricate geometries and often resulting in tool interference during the processing of highly complex structures. The production of complex structures is particularly challenging due to the limitations in design imposed by the manufacturing process itself, often requiring simplification for manufacturability. Moreover, these methods can be time-consuming and may not be cost-effective for producing small batch sizes or one-off, customized items.

AM, also known as 3D printing, has emerged as a revolutionary approach to address these challenges. The discrete mold-free unit-by-unit (e.g. point-by-point, line-by-line, layer-by-layer, and volume-by-volume) [56] manufacturing process offers the ability to create complex geometries with a high degree of dimensional precision and shape complexity, without the need for expensive tooling [57]. This technology eliminates many traditional design constraints, enabling the fabrication of parts with unique shapes and functionalities that were previously unattainable with conventional methods. The discrete manufacturing nature of AM also allows to produce components with varying material properties, which is particularly beneficial in industries like aerospace and automotive where weight and performance are critical.

Furthermore, AM facilitates mass customization by reducing setup costs, making it economically viable to produce small lots or even single units for specific users or applications. This is especially advantageous for creating customized products such as prosthetics or implants, where each item needs to be tailored to individual specifications. AM supports both high and low-volume production, making it a versatile manufacturing solution. AM also allows engineers to create integrated and intricate structural or functional ceramic components with greater design flexibility, effectively shortening the lead times and saving costs. It also enables

distributed manufacturing, which allows products to be manufactured closer to the point of need, further reducing transportation costs and lead times. The technology also promises to minimize waste during manufacturing due to its additive nature, aligning with sustainability goals.

In summary, while traditional ceramic forming methods have their merits, they are often hindered by the limitations in producing highly complex, customized parts and the challenges associated with machining hard and brittle ceramic materials. AM presents a viable solution to these issues, offering efficiency, design flexibility, customization, and the ability to create intricate structures with minimal material waste, thus paving the way for new possibilities in ceramic component manufacturing.

1.4 Brief Introduction to Ceramic Additive Manufacturing Techniques

AM has revolutionized the way ceramics are fabricated, offering a range of advantages over the conventional ceramic processing/shaping/manufacturing methods and other advanced manufacturing processes [48, 58–60].

The history of ceramic AM is a narrative of innovation and technological advancement. The earliest research in ceramic AM can be traced back to the late 20th century, with significant developments in the 1990s. Over the years, various techniques have been developed and refined for ceramic fabrication.

Here, different types of AM techniques used for ceramic fabrication are briefly summarized, according to the ISO/ASTM 52900:2021 standard [61] (Figure 1.4). Their working principles, controlling factors, and relevant research progress will be briefly covered and discussed in the following chapters.

- **Vat photopolymerization (VPP):** This method includes the linear scanning stereolithography (SL), planar photopolymerization such as digital light processing (DLP), two-photon polymerization (TPP), and volumetric additive manufacturing (VAM). These techniques use light to polymerize a ceramic slurry or resin in a vat. A dynamic mask or projection system is used to irradiate the light and cure the polymer in defined areas, building the part from the bottom up. They are suitable for creating parts with high precision and excellent surface quality.
- **Material extrusion (MEX):** MEX, such as direct ink writing (DIW) and fused deposition modeling (FDM), is an important part of ceramic AM. This method involves the extrusion of a ceramic material, often in a paste or filament form, through a nozzle to build up layers. The principle is based on the action of extrusion force during the printing process, which produces ceramic green bodies with relatively high solid content, eliminating the need for subsequent densification processes. Recently, a hybrid-process MEX technique such as DIW combined with UV photopolymerization as well as Embedded DIW has also been developed for high-quality printing of structures with geometries not achievable using common DIW approaches.

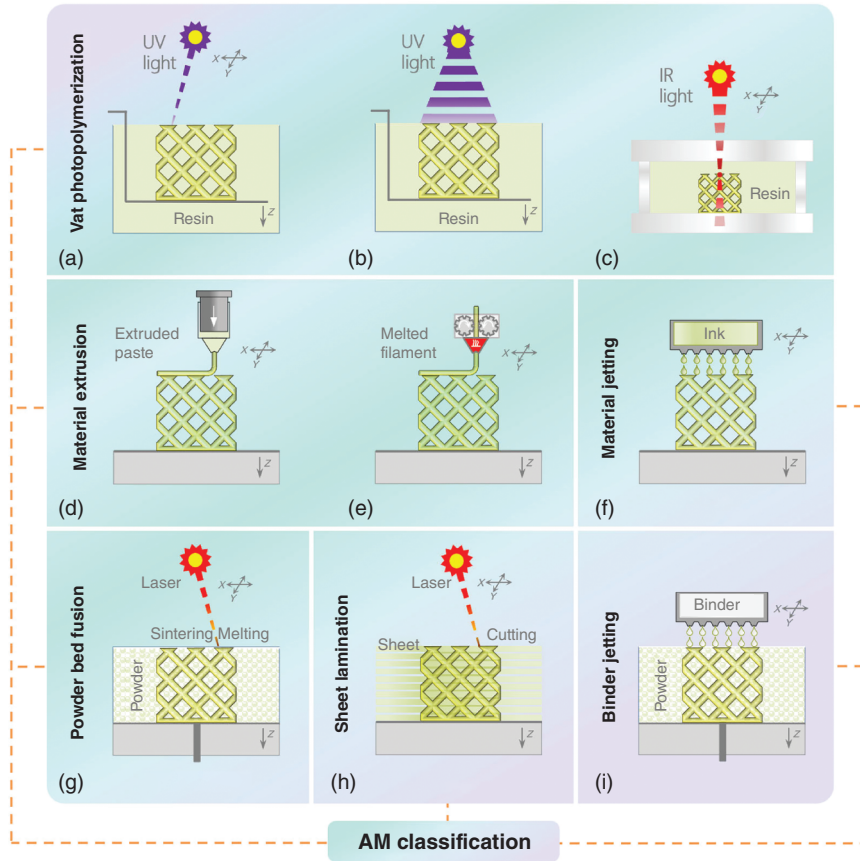


Figure 1.4 Major categories of additive manufacturing techniques suitable for ceramic fabrication. (a) SL. (b) DLP. (c) TPP. (d) DIW. (e) FDM. (f) IJP. (g) SLS/SLM. (h) LOM. (i) BJ3DP. Reference [62] / with permission of Elsevier.

- **Material jetting (MJT):** MJT involves the selective deposition of droplets of ceramic-binder mixed slurry onto a build platform. The droplets solidify to form a layer of the part, and the process is repeated until the part is complete. This method allows for the creation of complex geometries and can be used to produce parts with varying material properties or multi-material components.
- **Binder jetting (BJT):** BJT is a process in which a liquid bonding agent (i.e. binder) is selectively deposited to join the pre-deposited ceramic powder materials on the build platform. This process is different from the MJT method in that only the binder is released by the nozzles.
- **Powder bed fusion (PBF):** Techniques like selective laser sintering (SLS) and selective laser melting (SLM) fall under the category of PBF. These processes involve spreading a thin layer of ceramic powder (with secondary phase of binder powder in the case of SLS) in a bed and then using a laser to selectively fuse the powder based on the cross-sectional area of the desired part.

- **Sheet lamination (SHL)**, such as laminated object manufacturing (LOM), involves cutting and laminating thin sheets of ceramic material to build up the part layer by layer. This method is suitable for producing components with a high aspect ratio and can be used to create parts with complex internal structures.
- **Directed energy deposition (DED)**: It involves the deposition of ceramic materials using a focused energy source, such as a laser or electron beam. The material is fed into the energy beam, which melts the material as it is deposited, building up the part layer by layer. This technique is useful for repairing or building up ceramic components in a more controlled manner.

It should be noted that most of the above technologies, apart from PBF and DED, only produce green bodies which need to be further processed by debinding and sintering, therefore, with added complexities and costs. The possibility of obtaining ready-to-use ceramic additively manufactured parts, similar to metal or polymer-based components, is currently not viable due to limitations in the quality of the obtained products, which often contain unwanted defects such as voids or cracks.

The progression of ceramic AM research has been marked by a shift from single-material to multi-material approaches, allowing for the production of complex multi-material ceramic components with diverse geometries, compositions, and distributions. This shift has been driven by the need for components with varying properties across different fields, including aerospace, electronics, and communications industries.

Apart from the above major techniques, there are still some other techniques under development that are worth mentioning, such as robotic arm manufacturing. Of course, hybrid printing methods as well as multi-material printing methods are currently under the spotlight, as they enable the fabrication of complex ceramic components with integrated functional materials in a single build process.

As the individual ceramic AM techniques are discussed, it should also be noted that the feedstock required for successful ceramic AM might require special treatment and preparation. Ceramic powder quality is an important basis and guarantee for the consistency and reliability of high-performance electronic ceramics, structural ceramics, and bioceramic materials and products, and especially nano and submicron ultrafine powders have become the key raw materials for today's advanced ceramic industry.

Table 1.2 shows the history and development of AM technologies suitable for the fabrication of ceramic products and their origin, the requirements of the feedstocks, as well as the pros and cons of the individual techniques.

The future of ceramic AM lies in the development of multi-material and multi-functional ceramics. Research is focusing on improving the precision, strength, and functionality of ceramic parts, as well as expanding the range of materials that can be used in AM processes. Associated with this, there is a need to develop suitable approaches for the efficient and precise detection of internal defects in the produced parts as well as spotting any quality issues during printing, to avoid further processing of unsuitable components. The integration of different ceramic materials with

Table 1.2 Brief chronicle of ceramic AM techniques and their pros/cons.

Category	Technique	Time first appeared	Applied to ceramics	Pros	Cons
Vat photopolymerization (VPP)	Stereolithography	1984 [63]	1993 [64]	Good resolution, large printing size	Scattering, large material volume is needed
	Digital light processing (for 3D printing)	1996~ [65]	2010~ [66]	Suitable speed	Medium size
	Two photopolymerization	1997~ [67]	2006 (for polymer-derived ceramics) [68]	High resolution	Very slow, small size
	Volumetric additive manufacturing	2017 [69]	2022 (for polymer-derived ceramics) [70]	No staircase effect	Small size
Material extrusion (MEX)	Direct ink writing	1998 [71]	2001~ [72]	Suitable for lattice structures	Low resolution, low surface quality, anisotropy
	Fused deposition modeling	1989 [73]	1995 [74]	High density	Low resolution
Material jetting (MJT)	Inkjet printing	1950~ [75]	1995~ [76]	Suitable for layered structures	Low solid content
Binder jetting (BJT)	Binder jetting	1989 [77]	1990 [78]	Versatility in material choices	Low resolution, low surface quality
Powder bed fusion (PBF)	Selective laser sintering	1986 [79]	1990 [80]	Versatility in material choices, large printing size	Low resolution, complicated post-treatments
	Selective laser melting (or direct laser sintering)	1996 [81]	1999~ [82, 83]	Versatility in material choices, large printing size	Low resolution, stress concentration
Sheet lamination (SHL)	Laminated object modeling	1984~ [84]	1994 [85]	High density	Layer bonding issues, anisotropy
Directed energy deposition (DED)	Laser-engineered net shaping	1996 [86]	2008 [87]	Large printing size	Low resolution, low surface quality

varying properties, as well as the combination of ceramics with other materials like metals or polymers, is also an area of expanding interest. This will enable the production of more complex and functional components for high-performance applications in aerospace, biomedical, and electronics industries.

Additionally, there is a growing focus on the development of equipment and processes that can handle multi-material ceramic AM. This includes improving feeding modes and coupling various process technologies (so-called hybridization) to create more advanced and versatile ceramic components. As the technology matures, we can expect to see more innovative applications of ceramic AM, pushing the boundaries of what is possible in terms of material properties, part complexity, and functionality.

In conclusion, AM of ceramics is a rapidly evolving field with significant potential for growth and innovation. As research and development continue to advance, we can anticipate a future where ceramic components are not only more precise and complex but also more functional and tailored to specific applications. Table 1.3 provides a detailed comparison between the features and characteristics of different types of ceramic AM techniques.

1.5 Summary of the Book

The continuous research and development in ceramics processing are driven by the need for materials and components with superior properties for increasingly demanding applications. As technology progresses, it is expected that new fabrication techniques will emerge, further enhancing the capabilities and performance of both traditional and advanced ceramics. The aim of this book is to comprehensively address the unique manufacturability challenges of ceramics through advanced AM technologies, bridging fundamental material science with process engineering. It provides an authoritative synthesis of AM principles and cutting-edge innovations to enable reliable fabrication of high-performance ceramic components across various applications and materials.

In this book, **Chapter 1** introduces the foundations of ceramic AM, which fostered ceramics' critical role across industries, highlighting their unique chemical stability, thermal resistance, and biocompatibility. It contrasts traditional manufacturing limitations with AM's capacity for geometric freedom, setting the stage for ISO/ASTM 52900 classification of AM processes. **Chapter 2** covers stereolithography (SLA) and DLP for ceramics using UV-cured ceramic suspensions. It compares top-down and bottom-up configurations, emphasizing high resolution and surface quality. Challenges include resin formulation, shrinkage during sintering, and support structures, while VAM revolutionizes production by curing entire 3D volumes in seconds, eliminating layer interfaces and surface features. **Chapter 3** discusses BJT and MJT technologies. BJT uses powder beds selectively bound by liquid agents, while MJT deposits ceramic suspensions droplet-by-droplet (e.g. via piezoelectric or thermal printheads). Applications include gypsum models, sand molds, and technical ceramics, with challenges in nozzle clogging, droplet fusion,

Table 1.3 Detailed features and characteristics of different types of ceramic AM techniques.

Category	Technique	Forming principle	Energy source	Feedstock			Printing envelope	Resolution	Support needed	Speed	Surface quality	Overall cost
				Feedstock form	Feedstock requirements							
Vat photopolymerization (VPP)	Stereolithography	Photopolymerization	Light	Slurry	• Low viscosity		50 µm–100 cm	µm	Yes	★★★	★★★	★★
	Digital light processing	Photopolymerization	Light	Slurry	• Low viscosity		100 µm–50 cm	µm	Yes	★★★	★★★	★★
	Two photopolymerization	Photopolymerization	Light	Slurry	• Low viscosity • Transparency		1 µm–1 mm	nm–µm	Yes	★	★★★	★★★
Material extrusion (MEX)	Volumetric additive manufacturing	Photopolymerization	Light	Slurry	• Low viscosity • Transparency		100 µm–10 mm	µm–mm	No	★★★	★★★	★★★
	Direct ink writing	Extrusion	Force	Slurry	• High solid content		100 µm–100 cm	µm–mm	Yes	★★★	★	★
	Fused deposition modeling	Extrusion	Heat/force	Filament	• Filament		100 mm–10 cm	mm	No	★★	★	★★
Material jetting (MJT)	Inkjet printing	Binding	Force	Slurry	• Low viscosity		100 µm–10 mm	mm	No	★★	★★★	★

(Continued)

Table 1.3 (Continued)

Category	Technique	Forming principle	Energy source	Feedstock form	Feedstock require-ments	Printing envelope	Resolution	Support needed	Speed	Surface quality	Overall cost
Binder jetting (BJT)	Binder jetting	Binding	Force	Slurry/powder	● Binder required	10 mm–100 cm	μm–mm	No	★★★	★★	★★
Powder bed fusion (PBF)	Selective laser sintering	Fusion	Laser	Powder	● Binder required	10 mm–100 cm	μm–mm	No	★★★	★	★★★
	Selective laser melting	Fusion	Laser	Powder	● Good powder flowability	10 mm–100 cm	μm–mm	No	★★★	★	★★★
Sheet lamination (SHL)	Laminated object modeling	Binding	Laser	Sheet	● Sheet form	100 mm–100 cm	μm–mm	No	★★	★★	★
Directed energy deposition (DED)	Directed energy deposition	Fusion	Laser	Powder	● Good powder sphericity	10 mm–1000 cm	mm	Yes	★★★	★	★★★

Note: The number of ★ denotes the significance level.

and sintering shrinkage. **Chapter 4** details DIW and Fused Filament Fabrication (FFF) for ceramics. DIW relies on yield-stress ceramic inks for automated deposition, while FFF uses thermoplastic-ceramic filaments. Both methods enable complex geometries and multi-material structures but face challenges in shape fidelity, thermal gradients, and post-processing (debinding/sintering). Rheology and printability criteria are critically discussed. **Chapter 5** examines Selective Laser Sintering/Melting (SLS/SLM) and Electron Beam Melting (EBM) for ceramics. It distinguishes direct (full melting) and indirect (binder-assisted) approaches, addressing material constraints like electrical conductivity for EBM. Key challenges include dusting (powder bed instability), residual stresses, and achieving full density. Process optimization via parameter mapping is emphasized. **Chapter 6** explores laser-based DED for fabricating ceramic structures and composites. It highlights DED's ability to create monolithic ceramics (e.g. alumina and zirconia) and metal-ceramic functionally graded materials, enabling site-specific properties. Key challenges include thermal stress-induced cracking, limited material selection (excluding ultra-high-temperature melting ceramics), and scalability constraints due to inert atmosphere requirements. **Chapter 7** demonstrates hybrid AM (concurrent/sequential processes) and multi-material fabrication for ceramics, enabling freeform geometries, embedded features, and functional integration. It highlights strategies for co-sintering compatibility and stress management, with applications in heating elements, electronics, and SOFCs for next-generation multifunctional devices. **Chapter 8** comprehensively addresses computational design strategies, feedstock characterization protocols, and post-processing evaluation methods essential for ceramic AM. It details topology optimization for complex geometries, classifies feedstocks into powder-, liquid-, and bulk-solid-based systems with corresponding analytical techniques, and examines critical post-consolidation assessments, including anisotropic shrinkage control, thermomechanical stability, and defect minimization, to ensure structural integrity, especially in aerospace and biomedical applications. **Chapter 9** details industrial and consumer ceramic VPP differences, emphasizing industrial systems' material control, calibrated optics, and quality management for reproducibility. It explores multi-material LCM printing for enhanced mechanical properties and damage tolerance in complex ceramic components. **Chapter 10** explores diverse applications of ceramic AM, emphasizing its transformative impact across aerospace (lightweight satellite mirrors with integrated cooling channels), semiconductors (complex wafer-handling components), defense (high-performance radomes), energy (corrugated solid oxide cells for efficient hydrogen production), biomedical (customized implants and surgical tools), and environmental sectors (3D-printed coral substrates for reef restoration), leveraging technologies like stereolithography (SLA) to achieve unprecedented geometric complexity and functional integration. **Chapter 11** explores emerging frontiers in ceramic AM, focusing on green/smart design (recycled feedstocks, AI-driven process optimization), 4D printing (shape-morphing ceramics via differential sintering or hydrogel-ceramic bilayers), and 5D printing (multi-axis deposition for curved geometries), addressing sustainability challenges while enabling adaptive structures for advanced applications.

1.6 Conclusions

AM has fundamentally transformed ceramic fabrication, shattering geometric constraints and enabling unprecedented functional integration. From VPP's submicron precision to MJT's material gradients, each technology unlocks new possibilities in aerospace, biomedicine, energy, and other strategic sectors. While challenges like thermal cracking in PBF and debinding complexities in FFF persist, innovations in hybrid manufacturing and AI-driven process control demonstrate the field's adaptive resilience. The future lies in the convergence of sustainable material cycles, smart monitoring systems, and multifunctional designs – where ceramics evolve from passive components to active, adaptive elements, for instance, in quantum devices and personalized implants. As these technologies mature, they will not merely enable smart manufacturing of ceramics but will redefine their key role in an increasingly technologically sophisticated world.

AM has irrevocably transformed the fabrication landscape for advanced ceramics, overcoming intrinsic limitations of conventional methods such as geometric constraints, tooling costs, and machining brittleness. This book systematically discusses the major AM technologies: VPP, BJT, MJT, MEX, and PBF, demonstrating their unique capabilities in producing complex, high-performance ceramic components with tailored properties.

The future of ceramic AM research and development is likely to focus on improving the precision, strength, and functionality of ceramic parts, as well as expanding the range of materials that can be used in AM processes. The integration of different ceramic materials with varying properties, as well as the combination of ceramics with other materials like metals or polymers, is a growing area of interest, promising to open up extensive research opportunities in the realm of structural/functional ceramics.

- Key advancements highlighted include:
 - **High-resolution fabrication:** VPP techniques (TPP, VAM) achieve submicron features for micro-optics and biomedical devices, while MJT enables multi-material integration with droplet-level precision.
 - **Scalability:** BJT excels in large-format applications (e.g. architectural ceramics), and PBF supports high-temperature materials like ultra-high-temperature ceramics (UHTCs) for extreme environments.
 - **Material innovation:** Novel suspensions (DIW) and filaments (FFF) enhance sinterability, and hybrid processes (e.g. UV-assisted extrusion) combine speed with resolution and geometrical complexity.
- **Persistent challenges remain**
 - **Process-induced defects:** Thermal gradients in PBF cause cracking, requiring preheating or adaptive scanning strategies. Debinding/sintering complexities in BJT and FFF necessitate precise thermal profiles to avoid delamination. Furthermore, timely detection of these defects is of great importance to promote the upscaling of AM technologies into the industrial sector.
 - **Material limitations:** Non-oxide ceramics (SiC , Si_3N_4) demand inert atmospheres, while low-thermal-conductivity oxides (ZrO_2) struggle with thermal shock.

- **Standardization gaps:** Qualification protocols for critical applications (e.g. aerospace and implants) require further development.
- **Future directions emphasize**
 - **Smart manufacturing:** AI-driven real-time monitoring and closed-loop control to enhance reproducibility.
 - **Multifunctional systems:** Co-printing ceramics with metals or polymers for integrated sensors, energy harvesters, and bio-implants.
 - **Sustainability:** Recycling ceramic powders and bio-derived binders to reduce environmental impact.

In summary, ceramic AM bridges material science, process engineering, and digital design. It unlocks unprecedented opportunities for customized, high-value components across several key sectors, including aerospace, energy, and health-care. As technology matures, interdisciplinary collaboration will be pivotal to harnessing its full potential, ultimately reshaping the future of advanced ceramics manufacturing.

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