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ORIGINAL ARTICLE

Review of additive manufacturing methods for high-performance ceramic materials

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Abstract

Additive manufacturing (AM) has become a versatile and diversified technology that has made a huge difference in how things are being manufactured. Substantial growth has been observed in the development of ceramic materials for AM processes. However, ceramic parts manufactured by AM methods often exhibit deficiencies in mechanical properties and performance. Recent research developments have included improvement of performance and mechanical properties by introducing a material preparation process and additional post-processing techniques to improve the fabrication process. This paper contemplates and reviews the advancements made in AM techniques to fabricate high-performance ceramic (HPC) materials, also known as advanced ceramics. AM processes are classified as per ASTM standards and the technologies implemented are sub-listed. The principles, mechanical properties, advantages, disadvantages, applications, and limitations of each technology are described in detail.

Keywords Additive manufacturing · High-performance ceramics · Dry powder · Liquid slurry · Solid loading

1 Introduction

Additive manufacturing (AM), also known as 3D printing (3DP), is a fabrication process in which a product is fabricated layer-by-layer. AM provides flexibility to manufacture complex designs with relatively little effort and with reduced time and cost, allowing increased customization of products. As the manufacturing industry has shifted from mass production of single-use products to customized production to better meet individual customer needs [1] and increase in economic competitiveness, AM has opened ways to be more creative and explore new opportunities.

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Reviews of AM AM technology was introduced in the late 1980s. Since that time, much work has been published, reflecting the interest in, and importance of, the field. A number of survey and review papers have focused on AM methods, modeling approaches, control processes [2], and AM materials such as metal [3, 4], polymers [5], ceramics [6], and various composites [7]. Relatively few articles have classified AM processes based on specific international standards.

There have been some reviews related to ceramics' AM, but they have been limited to specific applications [8] or specific AM processes [9, 10], leaving other scientific accomplishments uncovered. One review paper that focuses on ceramic materials was found [11]. This paper reviews AM ceramic products from a fabrication process perspective (single- vs. multiple-step processes) and describes the pros and cons of each type of process. Relatively little work has focused on high-performance ceramic (HPC) materials. This paper aims to provide a comprehensive review of AM processes available to fabricate various types of HPC materials and to explicate the process parameters, heat treatment aspects, economic aspects, and applications of different AM techniques. Through the classification of AM techniques based on the material states and providing information on material synthesis, particulate aspects of the HPC materials, and available AM systems, this paper can assist AM practitioners from non-ceramic materials to select appropriate AM processes for specific HPC materials.

Definition of high-performance materials in ceramics Use of ceramic materials with high-performance properties has rapidly increased in recent years. However, until AM processes were introduced, companies had difficulty in meeting demand due to challenges in fabrication of high-performance ceramic (HPC) materials with complex geometries and personalized designs.

High-performance ceramic (HPC) materials exhibit characteristics such as high flexural and tensile strength, high thermodynamic stability (or resistance to heat), corrosion, abrasion, and oxidation. They are also extremely lightweight; have prominent dimensional stability even in thermal, corrosive, and abrasive environments; and have high energy–conversion capabilities.

Special HPC powder materials for AM processes have been introduced and are being investigated to overcome limitations and increase flexibility for various applications. Figure 1 depicts a few examples of AM applications using ceramic materials.

HPCs are typically classified into oxides, carbides, and nitrides [9]. Oxides are most widely used. Of these, Al_2O_3 is the most commonly used structural material due to its high chemical and thermal resistance; it is often used for applications such as insulation and biomedical devices [12]. Oxide parameters for the piezoelectric effect, thermal sensitivity, and electrical conductivity are exploited and used in lambda sensors (ZrO_2), actuators, crucibles (MgO), and shielding from high temperatures ($Al_2O_3TiO_2$).

Additive manufacturing of high-performance ceramics Conventional HPC manufacturing processes require multiple treatments such as powder synthesis, master forming (where basic or complex geometries are made), sintering to densify the structure, and finally, hard and soft machining to achieve the final part. Numerical control (NC) machining processes such as milling or grinding cause high tool wear and reduced material yields leading to high production costs. Due to limitations in geometry and shrinkage during sintering, use of HPCs has historically been precluded for certain applications. AM technologies can be used to overcome many of these limitations.

Using AM processes, HPCs can be manufactured using direct and indirect methods. In the direct method, ceramic material is deposited on the build area to form a layer and sintered immediately to densify the layer. This method does not require post-heat treatment. The advantages are that the final work piece has no shrinkage since it has already been densified and that the processing time is relatively short. However, a downside of direct manufacturing is that the work pieces tend to be porous ceramics and the surface roughness values are high, as compared with indirect AM processes. Indirect AM processes first form green bodies by binding the binder material with a structural material, followed by a sintering process to densify the green bodies before optional post-processing to clean residual uncured material. Indirect AM processes tend to produce highly densified parts with high surface quality and high-strength values, and they are built with high resolution. The downside is that shrinkage needs to be anticipated and additional fabrication steps are required to densify the objects.

2 Additive manufacturing methods for fabrication of HPCs

In advent of rapid prototyping (RP) technologies, several AM methods were introduced in the past 25 years. ASTM International has defined the standard classifications for the AM technologies. The AM processes are classified into seven categories: (1) vat photopolymerization, VP; (2) binder jetting, BJ; (3) material jetting, MJ; (4) material extrusion, ME; (5) powder bed fusion, PBF; (6) sheet lamination, SL; and (7) directed energy deposition, DED.

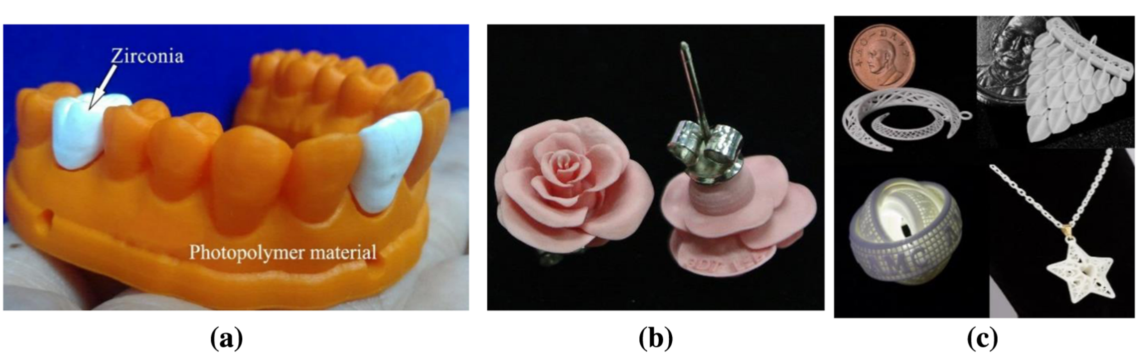

Fig. 1 A few examples of AM applications using ceramic materials. **a** Dental caps. **b** Jewelry. **c** Artifacts. Pictures from 3DT lab, Taipei Tech

2.1 Vat photopolymerization

Vat photopolymerization (VP) is an AM process where a liquid photopolymer in a vat is cured by projecting masked light from an active source [13]. The spectrum of light can be either normal visible light or ultraviolet (UV) light spectrum. There are two different approaches to fabricate HPC materials using VP process; the top-down approach and the bottom-up approach. Figure 2 represents the layout of the VP process with two different approaches.

Lithography-based ceramic manufacturing (LCM) developed by Schwentenwein and Homa [14] and Solvent-based slurry stereolithography (3S) developed by Wang et al. [15] stand as the best suitable HPC examples for the VP processes. The process parameters claimed by both the processes include the layer thickness, exposure time of the light with a relevant intensity level. Both the systems consist of a wiper blade that paves the slurry above the build platform while the thickness of each layer is controlled by moving the platform in a linear z-direction. In LCM and 3S processes, the green parts were built with the layer thickness of 25 μm and 20 μm, respectively. The light engine used in both the processes has a digital mirror device (DMD) resolution of 1920 × 1080 pixels. Each pixel resolution defines the tiniest detail that can be fabricated in the green part. With a pixel resolution of 40 μm in x- and y-directions, the build size of 76.8 mm and 43.2 mm was achieved. The pixel resolution defines the flexibility of fabricating the shell structure with a minimum wall thickness. A heat exchanger [16] was fabricated with a wall thickness of 0.1 mm which is not possible using conventional processes.

Process parameters The process parameters are primarily dependent on the ceramic slurry filling and viscosity of the slurry; by controlling the intensity of light and exposure time, the geometrical accuracy and overgrowth are controlled. An increase in exposure time is directly proportionate to the growth of curing depth and the over growth on the surface surroundings [17].

Heat treatment and post-processing After the fabrication of the green parts, they are subjected to debinding and sintering consecutively. The debinding and the sintering temperatures depend upon the binding material and the structure material used, respectively. For alumina and zirconia materials, the sintering temperature could range up to 1600 °C. During debinding and the sintering, it is necessary to sinter the parts under a controlled temperature to reduce the thermal stresses and avoid cracking. After sintering, the final objects obtained are highly dense ceramic objects with complex features. The final objects result in fine surfaces with a low R_a value and minimum porosity, which makes the parts facultative for post-processing like grinding, sanding, or infiltrating the pores.

2.2 Binder jetting

Binder jetting (BJ) is the process where a liquid binder is deposited selectively to join a powdered material. The BJ systems comprise of the cartridge that not only deposits the

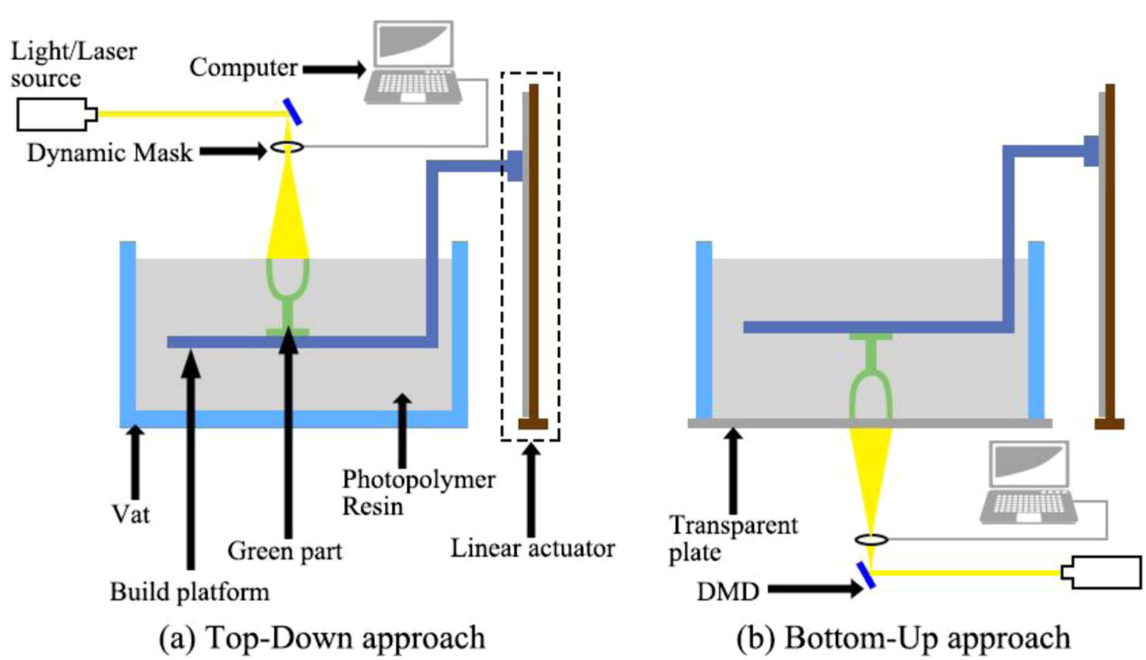

Fig. 2 Vat photopolymerization (VP) process layout. **a** Top-down approach. **b** Bottom-up approach

binder resin but also the ink like conventional 2D printers. For HPC, the BJ process is an indirect fabrication method where initially the powder particles are bonded using a binding material such as epoxy resin and starch, followed by sintering at very high temperatures causing the binding material to burn off while the structure material is bonded in multiple dimensions. This process also gives the flexibility of using different powders together to produce composites. Figure 3 depicts the layout of the BJ system.

Process parameters The BJ printing parameters are adjusted before initiating the print. The parameters like binder selection, layer thickness, heater temperature, spreading speed, binder saturation, and overhead heater travel speed are entered coded into the program based on the precursor powders instructed by the system developers [18]. In material selection and preparation, the material is put into the vessels and their height is adjusted. Then, let the printing process begin. During this process, a slight disturbance in the paving of layers can lead to catastrophic results. Hence, the layer resolution is determined to be set accordingly and the environment has to be undisturbed until the printing process ends. In BJ process, there are two methods of spreading the powder—either by using a blade, or by using a roller shaft. The roller shaft method has proven to be a more efficient way to spread the low mobility powder in high density and with consistent layer thickness. After the printing process, the green parts are carefully taken out of the system and depowdered and sometimes infiltrate filling agents (for example, wax and resin) to enforce of the parts.

Heat treatment and post-processing The ceramic green parts obtained after fabrication are necessary to be sintered under controlled temperatures to allow the objects to achieve their highest mechanical properties. The density of the final parts is dependent on the sintering time and temperature. For alumina material, the hardness was increased more than 6 times when the sintering time was increased from 2 to 16 h [19]. The BJ process is also not limited by any thermal effects, such as layer warping. The roughness and the porosity of the final objects are relatively higher than the ones obtained through VP processes. To fill the pores, post-processing steps could involve in infiltrating the porous objects to a solution in order to strengthen the parts [20]. The surface roughness can be improved by manual operations like sanding or grinding.

2.3 Material jetting

Material jetting (MJ) is a process in which droplets of the build material are selectively deposited [13]. The droplets are usually the combination of the molten thermoplastic suspension or wax along with the structure material. The droplets are deposited onto the surface continuously forming filament-like structures. MJ systems usually comprise of inkjet or similar cartridges, which have thousands of micro-size nozzles and deposit strings of droplets onto the build surface as per the layer pattern that is fed by the slicing software. The deposited droplets agglomerate the build material and solidify by cooling or by exposure from an external light source. Figure 4 represents the schematic layout of the MJ process.

There were several studies and publications that used inkjet technology with thermal drop-on-demand (DOD) to produce ceramic objects [21, 22]. The DOD is also achievable through piezoelectric technology to produce 3D structures [23]. The rheological characteristics of the ink are defined by the Reynolds, Weber, and Ohnesorge numbers (Re, We, Oh). Based on study of drop formation, generator, depositor, and the refilling system, the shape and

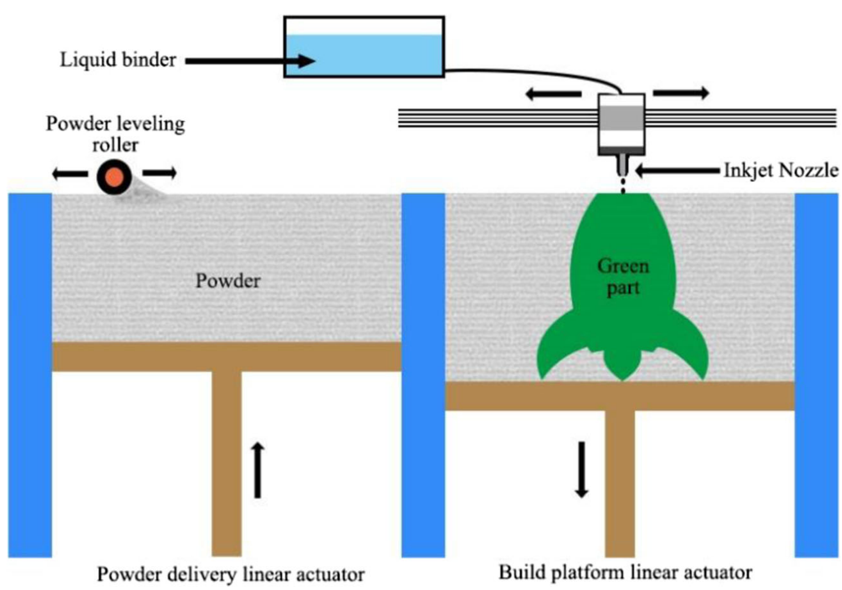

Fig. 3 Layout of binder jetting (BJ) process

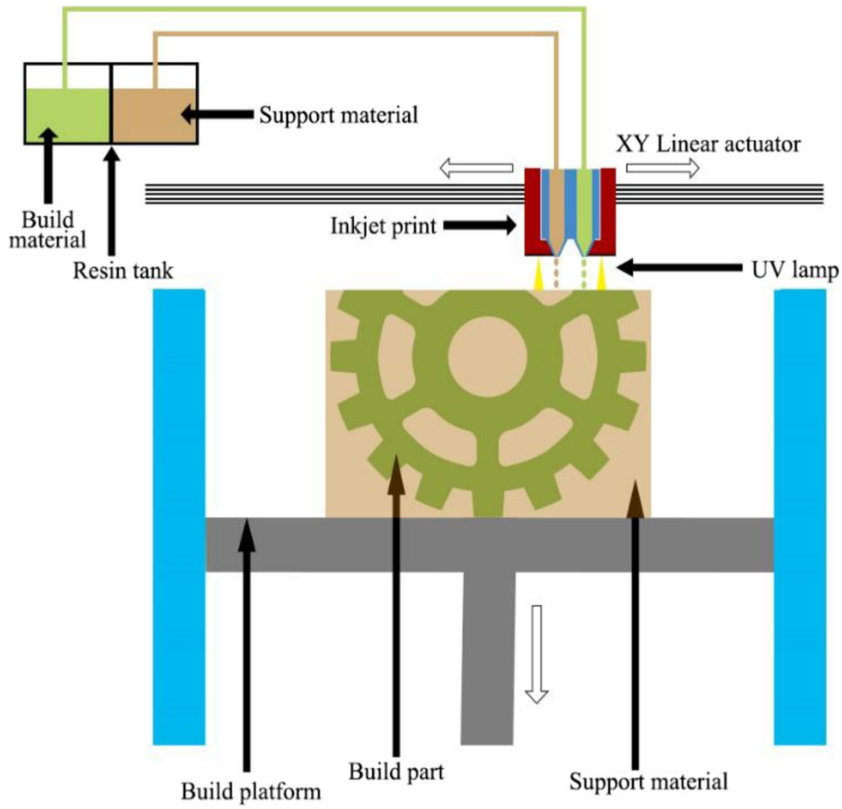

Fig. 4 Material jetting (MJ) process

form of the actuating waveform are designed for the piezoelectric DOD system. When the liquid drop affects with a planar surface, the drop deforms and spreads in multiple directions until it achieves a state of equilibrium. The individual drops when deposited on the substrate at a differed space a parallel-sided fluid track is achieved when the spacing is less than the maximum spacing between the drops [24]; where the maximum space between the drops is equal to the width of the droplet. In other cases, the deposition is not interacting with a drop-to-drop or having irregular edges or having bulged edges. After the liquid is dropped, it is important to let the droplet dry. The droplet is best dried by the coffee staining method as Deegan et al. presented. It occurs when the edge of the droplet is pinned, through the edge, the drop vapor evaporates. Hence, in some studies, an evaporating solvent is used to increase the density before sintering.

Overall, to produce stable ceramic workpieces using DOD technology, it has to be clearly noted that the ceramic suspensions must be well defined with the fluid and be able to pass through the droplet generator. Secondly, the proximity must be optimized to form a desired layer pattern by delivering the new suspension onto the previous layer or substrate. At last, the solidification by allowing the droplets to dry off before depositing another layer must be considered to produce a 3-dimensional object. HPC materials like zirconia, alumina, and silicon-based ceramic materials can be used.

The T3DP is an MJ process where the ceramic particles are combined with the thermoplastic suspension and cooled down when deposited to increase the viscosity [25]. Scheithauer et al. investigated the study of T3DP by using zirconia suspension and introduced the droplet fusion factor (dff) that can calculate the distance between the two droplets to form a continuous filament look-alike structure of droplets. The zirconia suspension used in this process is of nanoscale TZ_3Y-E with d_{50} = 0.37 μm and a purity of 90 wt.% ZrO_2 stabilized with Y_2O_3. A piezo-actuator controlling unit is used to dispense the drop at the rate of 1 KHz frequency through the nozzle.

Process parameters The process parameters of T3DP process include the droplet formation optimization by defining the rising slope, falling slope, the open time, the needle lift, and the dispensing system traversing speed. The suspension in this system is heated to 110 °C at the dispensing system. The two identical droplets are fused without overlapping when the distance between the two drops is equal to the diameter. The highly filled suspension has the lower height for the maximum filament suspension than the suspension with lower solid content. As the viscosity of the suspension is low, the heightening is also lower and the widening is inversely proportional.

The advantage of the T3DP process is that it delivers the homogenous distribution of the suspension that can result in high-density green parts before sintering. As the deposition of the droplets is selective, the properties of the final parts can be regulated flexibly by layer level. The solidification in this process is independent of the powders' physical properties as the solidification is dependent on the viscosity of the suspension while cooling down.

Heat treatment and post-processing The green bodies formed using MJ processes consist of wax or solvent that is necessary to be removed prior to the sintering process. The dewaxing is done by various processes like drying in the dry chamber under a controlled temperature for a certain time or putting inside the carbon black powder that can remove wax through capillary action [26]. After dewaxing, the objects are sintered at high temperature based on the filling material type. The sintering action is generally held for a certain time to burn the residual wax or any high molecular weight surfactant residues, followed by heating to the maximum temperature of the structure material in consecutive steps. Post-sintering, the objects obtained are tend to achieve highly dense ceramic components.

2.4 Material extrusion process

Material extrusion (ME) process is an AM process where the raw material is extruded through an orifice. This is the most common and economic AM process available [13]. ME systems are easy and less expensive to build. The materials used in ME processes can be classified into fused- or non-fused-type materials. For infused-type materials, the state of the material changes during the process, for example, solid to viscous paste and then viscous paste to solid. The solid material is fed through an extrusion head that consists of a heater and nozzle. The heater melts the solid material into a viscous paste that is extruded through the nozzle while traversing in the XYZ directions over the build platform. The extruded paste cools down with the surrounding environment and immediately solidifies. The non-fused-type materials remain in the same state throughout the process. Usually, the non-fused materials are in the form of a viscous paste that requires external pressure to make it flow. The examples of non-fused materials are clay (often mixed with porcelain) or other ceramic materials, concrete, etc. Figure 5 represents the ME process.

Process parameters The FDM process mainly relies on material composition that is being used. The material composition is desirable to have a tackifier to enable the tackiness and flexibility of the material; elastomer is used to provide elasticity, plasticizer to provide the plasticity for the filament to the spool, and wax to reduce the viscosity. The strength for the entire filament is given from the base polymer that is easily modifiable by the other constituents. In fused deposition of ceramic (FDC) process, a binder system with low viscosity, high strength, high strain, high modulus, and easily burnout

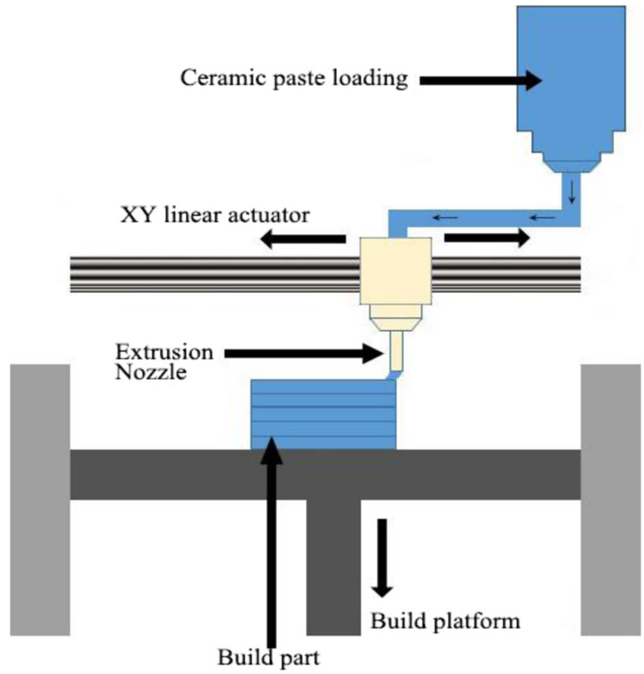

Fig. 5 Material extrusion (ME) process

was developed [27]. The binder system is composed of 55 vol.% of the ceramic powders, like titanium dioxide, mullite, and fused silica. With the nozzle temperatures between 200 °C and 265 °C, with suitable extrusion rate parameters, the printing process is initiated. In extrusion freeform fabrication (EFF) process [28], the feedstock comprises of Si_3N_4 in a volume of 55%, saturated elastomer of volume % of 25, paraffin wax, and fatty acid ester plasticizer each with a volume % of 10. The EFF process is similar to the multiphase jet solidification (MJS) developed by the Fraunhofer Institute of Applied Materials, Germany. This process can handle higher viscous materials through the feedstock and higher extrusion temperatures allowing to form many complex shapes.

Heat treatment and post-processing The green parts are formed by depositing the feedstock material as a semi-molten state through the liquefier's nozzle while the material is maintained between the temperatures of 200 °C and 265 °C. Once the green parts are formed, they are subjected to debinding and sintering processes. The liquid binder components are first removed by capillary action when set inside the dry alumina powder lesser than 200 °C. Followed by heating the parts over 200 °C, the remaining residual binder material is removed by evaporation and decomposition leaving porous green parts, followed by sintering the porous green parts up to the desired temperature which is 1600–1650 °C for alumina-based feedstock, causing densification and linear shrinkage of the ceramic parts. Ceramics can be printed with 100% infill density using ME processes but once the binder is burned out after sintering, the final workpieces tend to be porous. The porous voids can be filled using molten metals and form metal-ceramic composite functional parts [27].

2.5 Powder bed fusion process

Powder bed fusion (PBF) is the process where the powder particles are fused together selectively on the powder bed [13]. The fusing of the powder particles usually happens by focusing laser beams through a deflection Galvano mirror by scanning each layer according to the sliced pattern of the 3D model. The successive powder layer thickness can vary from 20 to 200 μm depending upon the particle size. Figure 6 represents the layout of the PBF process.

The process of fusing, also called a binding mechanism, is classified into mainly four types [29]: (1) solid-state sintering, (2) chemically induced binding, (3) liquid-phase sintering (partial melting), and (4) full-state melting.

i) Solid-state sintering (SSS) SSS is a thermal process that fuses the adjacent powder particles at 75% of the melting temperature. Many kinds of materials can be processed using SSS. However, preheating of the materials is required in this process to increase the diffusion rate of the atoms and keep in pace with the laser scanning velocity.

ii) Chemically induced binding In this process, the interaction between the laser and the material is very short and avoids the diffusion process unlike what happens in SSS. When the ceramic particle, say SiC, is subjected to high temperature, the partial disintegration of Si and C occurs. The free Si forms SiO2 due to oxidizing and acts as a binder between the SiC particles. After the infiltration using Si, a fully densified SiC is formed.

iii) Liquid-phase sintering (partial melting) This process is for a different binder and structural material where mostly metals are used as the binder particles and are smaller than the structural material. The technologies can be differed as per the structural material grain types that are used. For separate grains, as the binder material grains are smaller than the structural ones, there occur only small pores and the rearrangement of particles takes place through the capillary forces that cause movement of particles. For composite powder grains, they contain both binder and structural material within each individual powder grain. The composite grains result in higher green part density and lower surface roughness values. The third kind of powder particles is coated grains, where the structural material is coated with the binder material to ensure that the laser radiation is absorbed by the binder coating, leading to an effective bonding of the structural particle. This process is called partial melting because of the indistinct melting of the binder and the structural particles, where only the grains shell surface is molten.

iv) Full melting In this process, the structural material is completely melted by the laser beam and fused to form fully dense objects. This process is mainly used for metallic and ceramic materials [30].

Selective laser sintering Selective laser sintering (SLS) process can be implemented in two approaches to fabricate ceramic parts, i.e., direct SLS and indirect SLS. For the indirect SLS process, the laser beam hits the ceramic particles and results in solid-state sintering. Using direct sintering, the parts can be fabricated directly, but the high performances are not achievable. Several investigations were carried out to fabricate dense ceramic components through SLS processes. By using isostatic polypropylene (pp) as the binder phase for high purity α-alumina structural component and preheating the powder bed temperature just below the melting temperature of the binder, the green parts were fabricated [31]. In another study, a

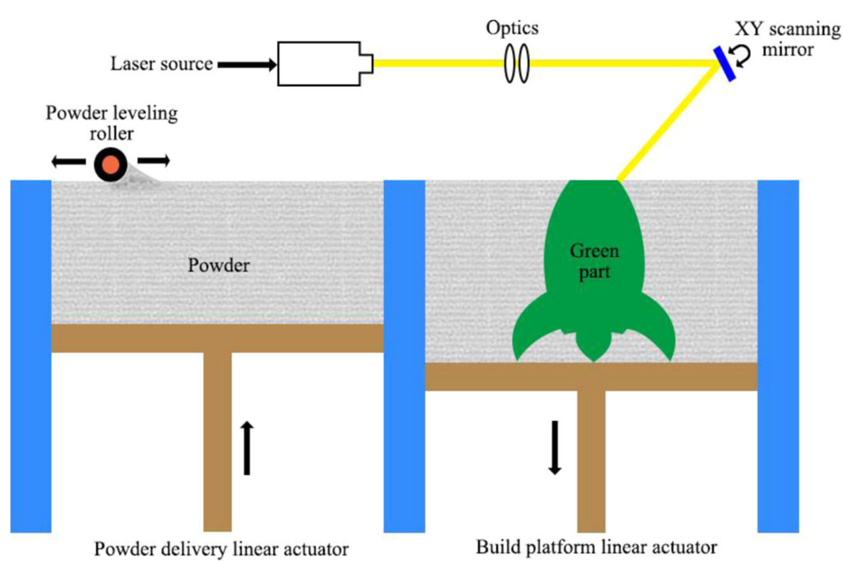

Fig. 6 Powder bed fusion (PBF) process

slurry-based SLS process was developed in which polyvinyl alcohol (PVA) was used as a binder to produce polymer-coated alumina parts [32].

Selective laser melting Selective laser melting (SLM) is a full melting–type SLS process where a pool of molten material is formed when subjected to laser radiation. It is capable of forming fully dense net-shape ceramic components without the need for post-processing. SLM has also shown significant improvement in product quality, processing time, and manufacturing reliability [30]. SLM was implemented to produce ZrO_2-Al_2O_3 ceramic components in which alumina powder is blended with zirconia to avoid crack formation and preheated up to 1600 °C [33]. In another study, the SLM process was implemented to investigate the key parameters to fabricate silica sand for sand-casting molds [34]. It resulted with an overall fabrication time of only 22 h to build, a 60 × 60 × 25 mm half cavity and 60 × 60 × 24 mm core half, and a dimensional accuracy of 0.4 mm.

Process parameters of the PBF process The important process parameters for PBF fabrication process are laser power, scanning speed, scanning spacing, layer thickness, and preheating temperature [31, 35, 36]. The energy density (*e*) is expressed as follows:

$$e = \frac{P}{H.v} \tag{1}$$

where P is the laser power, H is the scanning spacing, and v is the scanning speed. From Eq. (1), it is understandable that the laser power has the greater impact on the quality of the curing [37]. It is important to optimize the laser power to the critical value; higher laser power could melt and burn the binders while the lower laser power causes week bonding strengths.

In PBF processes, a blade or roller shaft spreads the powder above the previous layer. The material spreading also influences the formation of a dense and quality green part. The relatively small size of the powder can result in high-quality final parts as layers can be laid with a very high resolution. In the PBF process, the shape of the powder particle also plays an important role in forming dense objects. Near-spherical-shaped composite alumina ceramic parts can be produced with different binder materials through a temperature-induced phase separation (TIPS) process along with other conditions, and it was found that the parts built with low viscosity raw material produced high-density green parts and final parts [38].

Heat treatment and post-processing The fabricated parts are nearly densified in the SLS process but the residual binder material can be removed by heat-treating the specimen. After sintering, the relative density of the parts is increased and fully densified. Post-processing the green parts—such as infiltration process, polishing, thermal treatment, and coating—can improve their mechanical strength, surface roughness, and structural integrity, and decreases porosity.

2.6 Sheet lamination

Sheet lamination (SL) is an AM process where the sheets of materials are bonded together to form a 3D object [13]. SL is also implemented under the name of laminated object manufacturing (LOM) [39]. In this process, the sheets of the materials are bonded by applying pressure and heat using the coating of a thermal adhesive. A laser cuts the material into desired shape for each layer as per the sliced 3D model information. Figure 7 represents the layout of the SL process. The main advantage of this process is that it is very low-cost process, very little post-processing is required, and no support structures are required. The downside of this process is that the complex overhangs are difficult to be built, and the material that is subtracted in each layer during fabrication is not recyclable and wasted.

LOM is a basic SL process; many ceramic materials like monolithic silicon carbide (SiC), SiSiC composites, and aluminum nitride (AIN) parts have been produced. Using tape casting process, a thin layer of a ceramic sheet of large area can be cast and dried followed by punching and lamination [40, 41]. Using melt-infiltration method, a dense ceramic-metal composite can be fabricated [42, 43]. The metal melts into the porous structures of the ceramic and yields to in situ near-net-shaped and ceramic-metal composites. LOM process is also applied in fabricating MAX-phase ceramic materials [44]; M stands for metal, A stands for element group, and X denotes nitrogen or carbon. The materials used in this study are TiC and SiC with different ratios and processed by liquid silicon infiltration. The use of higher TiC content in the initial green tapes yielded to Ti3SiC2.

Process parameters LOM process parameters include mainly the preparation materials in the form of green tapes [41] or the pyrolized paper sheet and adhesive tape [45]. The lamination is carried out on the material at the bonding temperature. The layer thickness is defined by the sample thickness of each paper sheet. The process of laying new layers is done either automatically or by manual operation after hot pressing of each sheet.

Heat treatment and post-processing The green parts obtained are subjected to debinding and pressureless sintering to densify the parts. The pores that occur during the sintering process can be filled by infiltration methods to cover the gaps and increase the strength properties of the final objects [45]. The infiltration can be done by liquid silicon material at 1500 °C

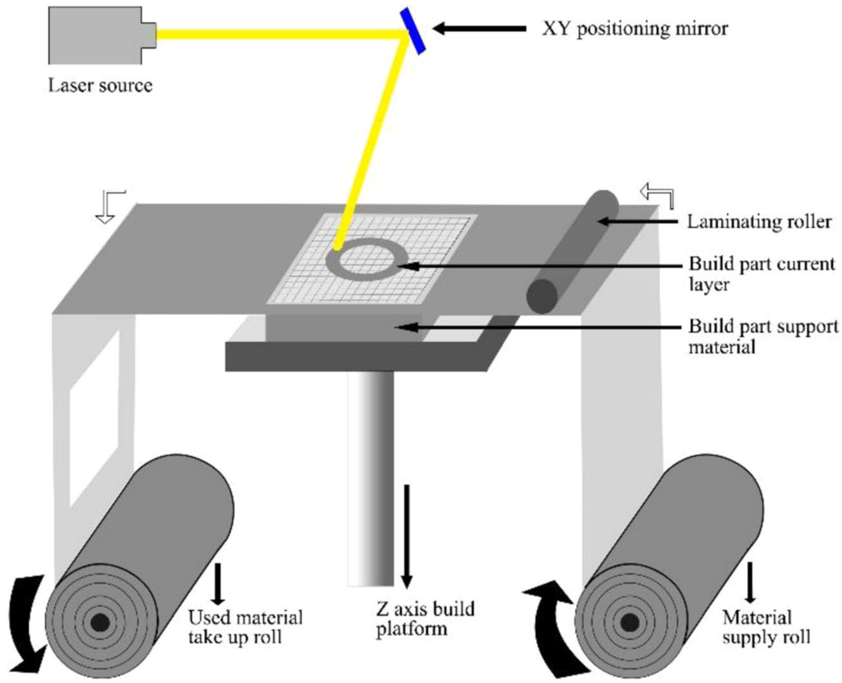

Fig. 7 Sheet lamination (SL) process

for 1 to 7 h. Due to the additional pyrolysis at 800 °C and spontaneous infiltration, the pore size distribution was well suited to the process and preserved the geometrical shape.

2.7 Directed energy deposition

Directed energy deposition (DED) is an AM process where focused thermal energy like a laser, electron beam, or plasma melts the material while depositing onto the surface [13]. DED is the direct fabrication method to produce ceramic objects. Ceramics with even up to 3000 °C can also be melted by focusing a high-power laser beam, and the substrates do not need binders for fusion. Figure 8 depicts the layout of the DED process.

Laser-engineered net shaping (LENS) is a DED process focused by the laser beam and produces molten material onto the surface area. The powder material is fed through the feeding gas that also acts as a coolant that solidifies the molten material as soon as it is deposited on the surface. LENS is much easier to control while achieving higher cooling rates. The main advantage of the LENS process is that it can remanufacture the parts and allows a minimal heat-affected zone. By using different powders carried in different nozzles and allowing them to react with different non-reactive gases, functionally graded materials can be produced.

Process parameters The key process parameters of LENS system are the laser spot width, laser scanning speed, and powder feeding rate [46]. The investigated results show that the increase in the laser power has a direct impact on the change in length and very little impact on the width. The surface roughness was also improved when the laser power was increased, making the molten pool to absorb more energy and increasing the fluidity of the material. When the laser power was increased from 175 to 200 W, the surface roughness decreased from 9.1 to 6.4 μm and the surface flatness decreased from 0.25 to 0.08 mm. The variation in deposition head scanning speed and the powder-feeding rate also affected the

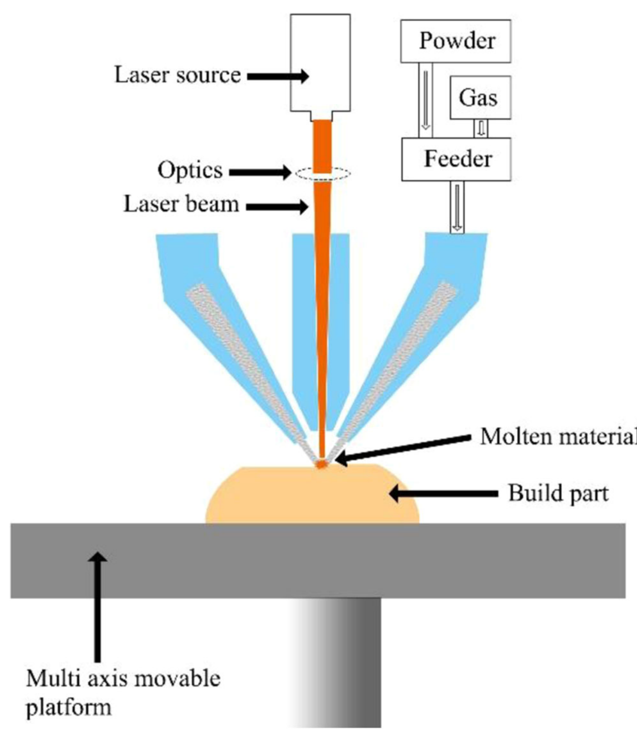

Fig. 8 Directed energy deposition (DED) process

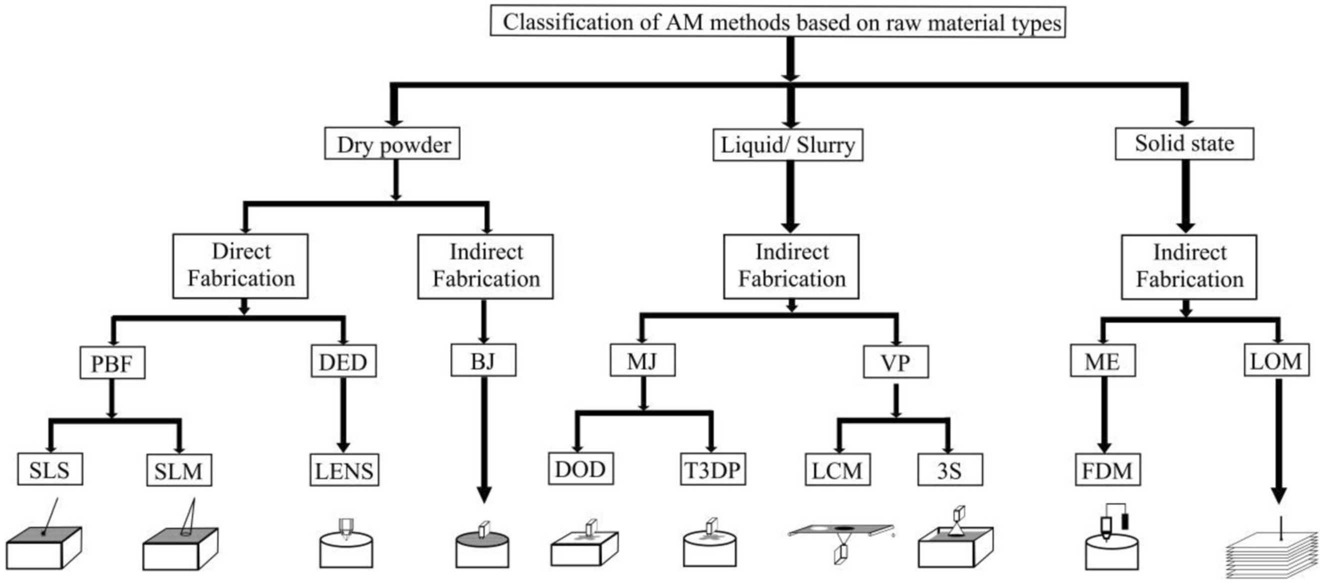

Fig. 9 Classification of AM methods based on raw materials

decrease in length, width, height, powder efficiency, and microhardness of the layer.

Post-processing Few 25 × 25 mm^2 thin-walled structure specimens were fabricated using LENS and subjected them to grinding, polishing, and gilding [47]. The samples are characterized to have the coarsening in the eutectic structure in the interlayer. As the grain size selected in this study was 200 µm, the porosity is visible between the divorced eutectic regions. LENS technology was also implemented to fabricate eutectic ceramic structures [48]. In this system, YAG ($Y_3Al_5O_{12}$) is doped into Al_2O_3 at the volume ratio of 55:45 to improve the microstructure and properties.

2.8 Classification and comparison

The materials used in AM processes are of different physical states with different rheological properties. A classification is provided in Fig. 9 to describe various different material states adapted by different AM processes, followed by Table 1 that describes the overview of the AM processes equipped with suitable layer deposition system. The materials can be usually prepared in three states: (1) dry powder, (2) liquid/slurry, and (3) solid state. The layer deposition is dependent upon the state of the material and can vary from process to process. Depending on the process, it is also possible to deposit multiple materials in one layer. The most common FDM process is able to deposit multiple materials through multiple extruders. Similarly, in the LENS, DOD, and T3DP by connecting multiple spray nozzles and dispersing orifices respectively to different feedstocks, multi-material deposition can be implemented within one layer.

Comparison of mechanical properties between the conventional and additive manufacturing AM has expanded to an extent of building the functional grade parts without additional requirement of tools, processing, and reduced lead-time. However, it has always been uncertain about the mechanical properties obtained by the AM processes which are able to meet the standards of those manufactured using conventional methods like injection molding, roll-forming, and sand casting. Table 2 provides a side-by-side comparison of the mechanical properties obtained by various conventional manufacturing and AM methods. The properties mentioned in the conventional manufacturing columns are acquired from the ISO and ASTM standard online material data publishing sources. From Table 2, it is observed that the flexural strength and fracture toughness values of most of the materials are comparably similar for both the manufacturing methods. Although manufacturing ZrO2 using conventional method can provide higher flexural strength values. It is very convincing that the oxide materials can be manufactured with high density and low porosity using VP process. Using VP processes, extreme overhangs and tiny shell structures can also be manufactured without yielding to cracks. However, the AlN manufactured using AM methods has less flexural strength. It is due to the LOM process, which in general has a very high layer resolution and poor bonding between each layers. Not all HPC materials have been used for manufacturing functional materials, but nitrides and carbides are mostly being used for research purposes [49].

Specifications obtained are from the materials' online material data publishing sources: Source 1: Ferro-Ceramic Grinding Inc., www.ferroceramic.com; Source 2: AZOM materials, www.azom.com; Source 3: MatWeb, material property data – www.matweb.com

Table 1 Overview of AM processes

	SLS	SLM	LENS	BJ	DOD	T3DP	LCM	3S	FDM	LOM
Binding mechanism	Laser sintering	Laser melting	Laser melting	Chemically induced binding	Chemically induced binding	Thermal adhesion	Light radiation	Light radiation	Thermal adhesion	Chemical adhesion
Layer deposition	Powder paving	Powder paving	Aerosol spray	Powder paving	Binder coated powder deposition	Extrusion based	Slurry paving on a thin sheet	Slurry paving	Extrusion based	Chemical adhesion
Multi material deposition	No	No	Yes	No	Yes	Yes	No	No	Yes	No

3 High-performance ceramic materials for AM processes

HPCs compete with metals due to their high-temperature resistance, high elastic modulus, and corrosive properties, which make them suitable for applications in hostile environments. Originally, ceramics were clay-based (what we now call classical ceramics); they were used in electrical insulators, whitewares for dishes, and tiles. However, with developments in ceramics, there are many different classifications of ceramic materials. In this review, HPC materials are classified into oxides and non-oxide materials. The non-oxide materials are carbides, nitrides, and borides. In this review, only oxides, nitrides, and carbides are considered for the AM processes. Oxides are the most commonly used materials that compete with non-oxide materials. Table 3 provides information about particulate aspects of the HPC materials in comparison with various AM processes.

Oxides In oxides, aluminum oxide (Al_2O_3) and zirconium dioxide (ZrO_2), also known as zirconia, have captured the market and have been used majorly as structural ceramics. The Al_2O_3 consists of a polycrystalline monophasic structure with a high oxidation state that does not allow it to age but does maintain resistance to corrosion and displays chemical inertness that are high-performance characteristics. These make the material suitable for biomedical applications [57]. ZrO_2 consists of the polycrystalline biphasic structure. The pure ZrO_2 is unstable at high temperatures because of its tetragonal phase, which is why it is necessary to be stabilized with a compound material like yttrium. In zirconia parts, the possibility of aging occurs and results in surface roughening because of the phase transformation from the metastable tetragonal phase into the monoclinic phase. Magnesium oxide (MgO) also exhibits high-performance characteristics and is applied in heaters, fireproof cables, etc. MgO has a high thermal conductivity and acts as a very good electrical insulator at very high temperatures. Silicates are subcategorized under oxides and are able to produce high performances with composite materials [58].

Carbides Carbides possess excellent wear resistance and oxidation resistance properties. For many years, silicon, titanium, boron, and tungsten that are metal carbides were used. Silicon carbide (SiC) has been a prominent HPC material throughout the ages due to its specific strength, stiffness, high corrosion resistance, and Young's modulus. It is inexpensive to synthesize and available in most complex engineering shapes. The use of SiC was widespread in the 1970s after introducing pressureless densification methodology [49]. SiC materials are also used as a composite with ZrB_2 and demonstrate higher strengths than 1000 MPa at room temperature and a fracture toughness of 3.5 MPa*m$^{1/2}$ [59]. Boron carbide B_4C

Table 2 Comparison table for the mechanical properties of HPC materials obtained by conventional and additive manufacturing technologies

HPC material type	HPC material	Conventional manufacturing			Additive manufacturing		
		Flexural strength	Fracture toughness	References	Flexural strength	Fracture toughness	References
Oxides	Aluminum oxide (Al_2O_3)	310–379 MPa	4.5 MPa*m$^{1/2}$	Source 1	427 MPa		[14]
					131.8 MPa		[19]
					363.5 Mpa		[32]
					148 ± 20 MPa		[31]
					228 MPa (3 PB)		[41]
						2.1 ± 1.3–4.4 ± 1.4 Mpam$^{1/2}$ (post-heat-treatment)	[50]
	Zirconium oxide (ZrO_2)	900 MPa	13.0 MPa*m$^{1/2}$	Source 1	731 MPa		[15]
					763 MPa	6.7 ± 1.6 MPam$^{1/2}$	[51]
						6.03 MPam$^{1/2}$	[52]
					427 MPa		[53]
	Silica (SiO_2)	110–200 MPa	0.62–0.67 MPa*m$^{1/2}$	Source 2	52.5 ± 2.6 MPa		[54]
Carbides	Silicon carbide (SiC)	324 MPa	4.0 MPa*m$^{1/2}$	Source 1	160 MPa		[39]
	Boron carbide (B_4C)	200 MPa	4 MPa*m$^{1/2}$	[55]	58.1–67.4 MPa	3.5 MPam$^{1/2}$ (theoretical assumption)	[56]
	Tungsten carbide (WC)	370–530 MPa	2–3.8 MPa*m$^{1/2}$	Source 2			
	Silicon-infused silicon carbide (SiSiC)	350 MPa	4.0 MPa*m$^{1/2}$	Source 3	123–150 MPa		[45]
Nitrides	Silicon nitride (Si_3N_4)	679–896 MPa	5.0–8.0 MPa*m$^{1/2}$	Source 1	597 ± 80–613 ± 12 MPa (unpolished and polished)	3.97 ± 0.34–7.07 ± 0.37 MPam$^{1/2}$	[28]
	Aluminum nitride (AlN)	428 MPa	3.5 MPa*m$^{1/2}$	Source 1	160 MPa		[39]

Table 3 Comparison of particulate properties of HPC materials utilized in various AM processes

Process	HPC	Particle size d_{50}	Purity (%)	Doping/stabilizer	BET specific surface area
VP [63]	Al_2O_3	0.2 μm	99.99		13.5 m^2/g
VP [54]	SiO_2	5 μm	98		
VP [64]	SiO_2	0.1–0.2 μm		NH_4OH	
VP [52]	ZrO_2	0.1~0.3 μm	> 94		14~18 m^2/g
VP [15]	ZrO_2	0.3~0.4 μm	> 94.3	3Y-TZP	7~10 m^2/g
BJ [53]	ZrO_2	1.23 μm			7.52 m^2/g
MJ [65]	B_4C	1.5–3.5 μm			6–9 m^2/g
MJ [51]	ZrO_2	0.09 μm		3Y-TZP	7 ± 2 m^2/g
MJ [66]	Al_2O_3	0.4 μm		Hypermer LP1 and stearic acid	8.2 m^2/g
ME [67]	ZrO_2	0.3 μm		3 mol% Y_2O_3	7 ± 2 m^2/g
	Al_2O_3	1–1.7 μm	99.8		
ME [68]	Al_2O_3	0.5 μm	99.8		8.9 m^2/g
PBF [35]	Al_2O_3	0.4 μm	99.7		
PBF [31]	Al_2O_3	0.3 μm	99.99	Xylene	9–12 m^2/g
PBF [32]	Al_2O_3	0.5 μm	99.8		
DED [47]	Al_2O_3	40–90 μm		3 wt% Y_2O_3	

has hardness values similar to that of diamond. B_4C materials are used in lightweight armors because of its low specific gravity and high hardness.

Nitrides Nitrides are known for their electrical applications, internal combustion (IC) engines, turbine blades, crucibles for molten metals, etc. The silicon nitride Si_3N_4 has grabbed more attention as a structural ceramic for biomedical [60] and automobile applications. The aluminum nitride (AlN) is majorly focused on the electronic integrated circuits applications where it is used as substrate layers and for thermal management applications. AlN has weak atomic bonding that can accelerate the sintering and fusing processes, but it exhibits only moderate hardness and modulus values. However, by using alkaline earth compounds like yttria, calcium oxide, yttrium fluoride, and calcium fluoride as additives, high sintering densities with desired electrical and thermal properties can be achieved. Boron nitride (BN) has three isostructural forms known as amorphous, hexagonal, and cubic similar to carbon. Due to its higher thermal conductivity than copper, it is used as a heatsink in electronics applications [61].

3.1 Particulate aspects of HPC materials used in AM processes

In the recent trends, the HPC materials are abundantly available with all the suitable specifications required for the manufacturing process. By contrast, the particulate engineering aspects have become very important in choosing the materials before preparing the feedstock for various AM processes. To achieve the dense layers while fabricating, the suspension or powder substrate is supposed to have good colloidal stabilization while preventing coagulation and pore agglomeration. If the suspension is in liquid or wet slurry state, the particles must have good disintegration when subjected to liquid medium. The key parameters while choosing materials are particle geometry size, surface area distribution, impurities and additives, composite materials, etc. Table 3 provides the particulate properties of HPCs used in different AM processes.

Geometry size The powder particles' geometry size can directly affect the quality of the final part. Based on the geometrical dimensions of the powder particles, viscosity of the slurry suspension is defined and the layer resolution is affected in the powder-based processes. Specifically in VP, MJ, and BJ processes, the fine particles can fill the voids before sintering and produce high-density green parts. Nevertheless, the binder material quantity is also a key parameter for high-density parts.

Surface area distribution The surface area of the particles is directly proportional to the geometrical size of the particles. In a fine-compact small-size ceramic powder, the particles are densely packed contacting with the surface boundary of the neighboring particles. As the powder size increases, the contact formation of the neighboring particles decreases and large area of the surface remains non-contacted, leading to highly porous structures. During the sintering process, the formation of the neck between the particles exhibits the physical strength of the structure.

Doping stabilizers and additives In spite working under harsh mechanical loads and thermal shock conditions, pure ceramic materials tend to exhibit their limitations through brittleness and low fracture toughness. Pure ceramics tend to phase-change from monoclinic to tetragonal (~ 1100–1200 °C), then tetragonal to cubic (2200–2400 °C) state making the part prone to cracking due to the internal stresses. By adding impurities and additives, the phase transformation can be toughened in the ceramic materials. For example, the zirconia materials are usually added with yttria, ceria, and magnesia materials. The additives stabilize the parent material during the phase transformation and exhibit higher fracture toughness value than before the transformation [62].

Impurities The purity of the ceramic materials used in the AM processes is usually very high but never 100% pure. They tend to have 0.1–5% of impurities, including dispensers and doping stabilizers. The impurities are helpful to maintain the charge balances that can consume large amount of energy required which can be minimized by the non-stoichiometric redistribution of the atomic charges, which is by adding the impurities that react through solutes, oxidation, and reduction processes. Impurities can relatively decrease the viscosity of the suspension with increase in temperature.

Composites The composite materials are particulate-reinforced or combinations of oxides/non-oxide ceramics. The composite ceramics can exhibit higher fracture toughness and mechanical strength values than the conventional ceramics. The embodiment of the reinforced material has a higher elastic modulus than the original material. The composites can also be induced as infiltrates into the pores of the final objects providing additional mechanical strengths [45].

From Table 3, it is observed that the particle sizes used in different VP processes are very similar to each other and the difference in purity does not have impact on fabricating high-resolution parts. In fact, the less pure ceramics tend to provide high-resolution final parts due to the stability achieved during the sintering process. Apparently, the MJ processes tend to use materials with lowest d_{50} values to disperse the material through the micro-orifices. By contrast, in DED process, the particle sizes did not affect the fabrication process and the mechanical properties where the particles are dispersed through aerosol spraying method. From Table 3, the zirconia particles with the huge difference in particle sizes tend to have similar specific surface area. This is possibly due to the non-uniform distribution of the particles within the powder/suspension.

3.2 AM processes available for HPC materials

In spite plenty of research methods exhibited high-quality HPC parts, there are not many successful companies using AM techniques for fabricating HPC materials. Table 4 provides information about the commercial AM systems available worldwide. It is observed that oxides are the most commonly used HPC materials, and most of the AM techniques are suitable to fabricate oxide materials, specifically alumina and zirconia.

3.3 Synthesis of HPC materials for AM processes

The production of ceramic powders in nano-sized particles is very important for the fabrication of high-quality parts. Lately, the demand for high-quality fabrication within low-cost methods has increased, and this has motivated many industries and academicians to develop innovative techniques to produce HPC materials. The cost of production of high-quality powder for low-cost AM processes has always conflicted with each other. For instance, it is easier to produce high-quality powders by acquainting additional processing steps, but each additional step increases the price of the powder material.

Conventionally, the ceramic materials can be produced in bulk amounts through many processes like Bayer process [69], hydrothermal methods [70, 71], and combustion-based synthesis [72]. Recently, arc discharged plasma technique and pulverization-based study were implemented to prepare nano-AlN powders from Al wires [73] and oxide powders like $SrTiO_3$, TiO_2, and $BaTiO_3$, respectively. However, the ceramic feedstock for AM processes requires more than just preparation of the structure materials. Along with the structure materials, the binder material plays a key role in fabricating dense parts. In binder feedstock, the binder must be easily removable from the green part with minimum pyrolysis residue. In suspension-based feedstock, the dispersant is necessary to distribute the particles homogenously. Based on the state of the material, the feedstock properties are adapted. Table 5 provides the feedstock information of three different states of materials, i.e., dry powder, liquid/slurry, and solid state. In the dry powder feedstock, the rheological property is measured based on the powder flowability and ceramic packing, while in the liquid/slurry and solid state, it is measured as per the viscosity and the shear stress. The suspensions are prepared using different mixing mechanisms to form a homogenous mixture at their suitable temperatures.

4 Economic aspects and applications of HPCs fabricated by AM processes

AM techniques have brought a great deal in manufacturing in terms of economic aspects. AM is replacing the centralized assembly lines for prototyping and manufacturing low-volume components. The cost for producing a component using AM techniques can be divided into cost for feedstock and cost for fabrication. Table 6 provides the cost for

Table 4 Commercial AM systems available for HPC materials

AM processes	Systems and processes available for HPCs		
	AM systems	Process	Materials
Vat photopolymerization (VP)	Lithoz Cerafab 7500	LCM [14]	Al_2O_3, ZrO_2, Si_3N_4
	3D Ceram - Ceramaker	Using laser and photosensitive ceramic resin	Al_2O_3, ZrO_2, Si_3N_4, ZrO_2 8Y, HAP, ATZ, SiO_2,
	DWS – XFAB 3500	Tank translation technology (TTT)	Custom materials
	Prodways Promaker V6000	MOVINGLight technology	Al_2O_3, ZrO_2, HAP, $Ca_3(PO_4)_2$
	Admatec – Admaflex 130	Admaflex technology	Al_2O_3, ZrO_2 ATZ, HAP, SiO_2
Binder jetting (BJ)	ComeTrue M10	ComeTrue Binder Jetting (CBJ) – inkjet-based process	TP 80, TP 81
	Kwambio - Ceramo one	Ceramic binder jetting	High-performance composite
Material jetting (MJ)	CeraDrop – CeraPrinter F series	Inkjet and aerosol jet	Multi materials
	XJET - Carmel	Nanoparticles liquid dispersion	Technical ceramics
Material extrusion (ME)	WASP - DeltaWASP	Non-fused material extrusion	Al_2O_3, ZrO_2, clay, porcelain
	StoneFlower	Non-fused material extrusion	Clay
Powder bed fusion (PBF)	Osseomatrix	Direct laser microfusion	HAP, $Ca_3(PO_4)_2$
	VTech – VT C500	SLS	Al_2O_3
	3DSystems – Phenix PXL	SLS	Al_2O_3, cermet
Laminated object manufacturing (LOM)	CAM - LEM	CL - 100	Al_2O_3, ZrO_2, Si_3N_4
Directed energy distribution (DED)	Optomec - LENS 450 (customized) [54]	LENS	Al_2O_3

Source: Material specifications obtained are from the system manufacturing companies- Lithoz, 3D Ceram, DWS, Prodways, Admatec, Comptrue 3D, Kwambio, CeraDrop, XJET, WASP, VTech, 3DSystems, CAM, Optomec, StoneFlower, Osseomatrix

fabricating a component using AM techniques with their build size configurations. The low-cost feedstock means the material is commercially available for low cost. The fabrication cost includes the operation cost and processing and post-processing cost including the capital expenses. In contrast, the AM is economical for mass customization and manufacturing certain number of components but not for mass production. For low-cost production/prototyping, FDM and LOM are suitable while LENS and PBF are able to deliver larger volume components with higher mechanical strengths for higher costs; the BJ process can deliver larger build volumes for relatively lower prices but reduced mechanical strengths. Although AM processes can deliver bigger build volume, it is still challenging to fabricate a large component without deformation or cracks. Instead, the bigger build volume AM systems can be utilized to make multiple smaller components in one batch. This makes AM more suitable for batch production

4.1 Applications

Over the past few years, there has been great progress in fabricating HPC materials using AM methods, but it has been most suitable for prototyping and production in low volumes. AM has offered great potential for mass customization for orthopedic implants and automobile parts, and for applications in various other fields which are listed below.

Automobile and turbine manufacturing In the automobile and turbine manufacturing industries, it is necessary to push the material limits to its maximum to improve their performance efficiency. For example, a gas turbine is required to operate at 1200 °C. As it is necessary for the materials to be resilient, durable, and non-reactive to the environment, HPCs are the best suitable materials for this application. So far, HPCs are being used as a thermal barrier coating and as a structural material [75], exhaust gas flaps, plain bearings, sensors, sealing, sliding, storages, etc.

Biomedical application The ceramic materials have a special class of ceramics for biomedical applications and they are known as bioceramics. Alumina and zirconia are the most basic materials that are bioinert in this class. There are also bioactive materials like hydroxyapatite or bioactive glasses used in applications like knees, tendons, ligaments, repair for jawbones, and spinal fusion [76]. The bioglass implants were successfully implanted for low load bearing bone restoration using laser AM processes [77]. Using AM-fabricated bioceramic materials, antibiotic drugs are also delivered to treat bone infections [78]. AM has many case studies for creating custom implants to treat the reconstruction of

Table 5 Feedstock information of the AM HPC materials

Feedstock state process	Feedstock composition			Rheological and physical properties
	Material	Binder material	Other materials	
Dry powder: PBF – SLS, SLM; DED – LENS	Al_2O_3	Hydrolyzed PVA polymer (organic or inorganic)	Defoaming agent; epoxy resin E06 polymer	Powder state; good flowability
Dry powder: BJ	Ti	ZB60 3D Systems	TiB_2; 19 wt% bisphenol-A ethoxylated diacrylate (BAE); 2 wt% cellulose acetate butyrate (CAB); 2 wt% phenylbis (PI) phosphine oxide and acetone	Powder state; good flowability
	Si	Modified starch; epoxy-diane non-curing resin ÉD 20	Sulfanol as surfactant	
Liquid/slurry: MJ - inkjet	Al_2O_3	Paraffin wax	Dispersant: Hypermer FP1 or Hypermer LP1, Uniqema or stearylamine or stearic acid (1-octadecanoic	Wax viscocity: 2.8 mPas; filtered through 30-μm steel mesh; shear rates of 3–300 s^{-1}; viscosity: 0 to 40%wax–3–38mpas
Liquid/slurry: MJ – direct ink writing [65]	B_4C		5 vol.% cationic polyelectrolyte dispersant, 5 vol.% hydrochloric acid (HCl), and balance of water	pH 5.35–5.91; bob geometry fixture gap 150 μm; shear rates 0.01–35 s^{-1}
Liquid/slurry: VP	Al_2O_3	Diacrylate - diacryl 101	Ethanol, methylethylketone (MEK)	Viscosity: 3.6Pas; good homogeneity due to solvent evaporation
	SiO_2		Irgacure 184 (1-hydroxy-cyclohexyl- phenyl-ketone)	After ball milling, shear rate: 0.1 and 100 s^{-1}; homogeneous slurry
Solid state - ME - FDC	$3Al_2O_3$, $2SiO_2$; SiO_2; TiO_2; Al_2O_3	Polypropylene	44% polypropylene + 13.9% elastomer + 18.7% plasticizer + 7.8% tackifier + 15.6% wax	Filament diameter: 1.78 mm. Nozzle temperature 235–237 °C; flow rate 130%
Solid state - ME [74]	ZrO_2		Microcrystalline, wax stearic acid	Shear rate 1000s^{-1}; extrusion rate 10 mm/s; shear stress 2×10^4 Pa; viscosity 20Pas
LOM	Al_2O_3 - Ti			70% dense rectangular (16 × 16 × 20 mm) and cylindrical (18 mm dia × 20 mm height) sheets
LOM	SiC, AIN	Polymeric binder		Sheet thickness 150–175 μm, 300–325 μm, widths 20 cm, lengths 1 m

Table 6 Economic aspects of AM processes for HPC materials

Process	Cost of feedstock	Cost for fabrication	Build volume
SLS	Low	High	Medium, Large
SLM	Low	High	Medium, Large
LENS	Low	High	Small, Medium, Large
BJ	Low	Medium	Medium, Large, Extra large
DOD	High	Medium	Small, Medium
T3DP	High	Medium	Small, Medium
LCM	Low	Medium	Extra small, Small, Medium
3S	Low	Medium	Extra small, Small, Medium
FDM	Low	Low	Medium, Large, Extra large
LOM	Low	Low	Medium, Large

Extra small, < 1mm; Small, 1–10 mm; Medium, 10 mm–0.1 m; Large, 0.1–1 m; Extra large, > 1m

craniofacial defects. The 3D models of the facial structures are obtained from the CT-scan data. Then the implants are designed according to the environment and fabricated using a suitable AM process. This has reduced the operating time and increased the success rate of the implants [79]. Using BJ process cast orthopedic implants [20], different porosity Si_3N_4 ceramics [80] and many other bioceramic scaffolds [81] can be fabricated at very economical price.

Dentistry Over the years, ceramics, especially oxides, were most fondly used for dental applications such as for crowns, bridges, and veneers. They are implemented by either using all-ceramic or with metal restorations. Several processes have investigated the use of dental ceramic fabrication using AM methods and reported the issues, inaccuracies, and downsides of this processes [82, 83].

Electronic applications Ceramic materials are used for their insulating, semi-conductive, piezoelectric, and magnetic conductive properties in various electronics. They are widely used in capacitors, sensors, actuators, and many other applications. Though not all high-performance properties of ceramics are required in these applications, they are mostly used for their dielectric properties, durability, and non-reactive property. The application of AM comes in fabricating the highly complex semiconductors with a controlled number of layers with multiple materials and geometric resolution. SLM technology was investigated for the process development for the generation of conductive patterns on ceramic substrates [84]. Using aerosol-based and voxel-based fabrication, it is also possible to fabricate on uneven surfaces by the direct wire, also called direct writing (DW) technology [85, 86].

Aerospace applications The applications of AM in aerospace include fabricating ultra-high-temperature ceramics (UHTCs) (> 2000 °C) which are not possible to be manufactured using conventional methods. The elements of miniature sensors, turbine components, electrode supports, spark plugs, flange insulation, etc. that have complex requirements can be fulfilled using AM processes. UHTCs are used in hypersonic engines that are built with improved thermal conductivity, toughness, oxidation resistance, strength, and emissivity [87]. The scaled down models of missile nose cones are fabricated with alumina and zirconia boride materials using FEF process [88], which is an indirect method.

5 Technology roadmap for additive manufacturing of HPC materials

Recent developments in additive manufacturing have been very exciting. The use of ceramic materials has also rapidly increased over the past 5 years. Their tremendous potential is untapped when paired with AM systems (Lithoz, Admatec, etc.) offered by few commercial systems and many academic research projects. Numerous patents have been issued recently and many more are in process. AM has driven the concept of mass customization and can now be used to produce functional parts directly with a precision equal to conventionally manufactured parts. The costs for AM systems and production have fallen in the past few years due to new processes, decrease in raw material prices, and demand in the market; nevertheless, it is still expensive compared with conventional methods and not suitable for mass production. The supply chain for AM methods is relatively versatile. The number of stages in a supply chain is reduced by enabling direct manufacturing of parts that used to be manufactured in multiple components. It has also enabled the use of desktop-sized systems that can be used in-house, which removes or reduces the need for warehouses, transportation, and packaging. AM has also reduced health and occupational hazards—such as fluid spills, wasted chip powders, extreme noise, and air pollution—that commonly result when using conventional methods such as casting and forging. However, AM may create new health problems. Environmental effects and human safety need to be addressed and regulated as the use of AM methods increases.

Most AM methods used for fabricating HPC materials are powder-based. Powder-based methods face issues when building parts with high density. Hence, the use of slurry-based technologies has been increasing more rapidly; but due to internal stresses during green part formation, the parts are limited to small sizes. Large-sized HPC parts are built using laser-based systems that are not yet cost-effective. On the other hand, the AM processes are replacing the steps for additional tooling steps like grinding and milling for fabricating functional parts of small sizes. For conventional methods, design for fabrication has always been a limitation, but AM methods overcome these issues in fabricating personalized implants with flexibility in design and durability. Using DED processes, it is now also possible to remanufacture or repair the old parts to extend their lifespan. AM has the capability to build any kind of complex part while using less energy and raw materials. Yet, many innovative processes have not been transformed into commercial systems due to inefficient and complicated ecosystems. With bigger growth in demand for mass personalization, a strategic ecosystem can be framed.

Using laser-based AM methods for direct fabrication, large-sized ceramic composite parts can be produced with high quality, but monolithic ceramic parts still lack high-performance properties when using these methods. Hence, it is also required to adapt classic powder processing methods to form monolithic ceramic components using AM methods. So far, AM has been redefining the standards of final parts using polymers and metals as composites and reinforcements. However, standards for metallurgical and mechanical properties are yet to be established for components based on these alternate materials. Needed are more research facilities, increased collaboration between academic researchers and industry, skill development, standardization, and materials research and development.

6 Conclusion

In this paper, innovative and potential AM processes available for HPC materials are discussed along with their process parameters, heat treatment aspects, material synthesis and particulate aspects, applications, and future works which are addressed. AM has versatility in terms of materials and process control, but the majority of applications have utilized only single materials. The cost of materials is one of the biggest factors affecting the price of the final part. Hence, it is also important to introduce novel materials with improved properties that can be produced in-house location. This can make AM become an integral process that utilizes both novel and commonly used materials to meet desired product requirements.

Even though some materials, such as composites (metal and non-metal mixtures), have expanded potential applications with improved mechanical properties, AM processes are still considered a niche technology. Several attempts have been made to commercialize various AM technologies, and ceramic components have been successfully delivered in a few cases. With the advent of new material synthesis and fabrication techniques and an adequate ecosystem, AM can be successfully commercialized and utilized for rapid mass manufacturing instead of rapid prototyping. This paper has aimed to enable readers to acquire a thorough understanding of AM processes for ceramic materials and to choose the right technique to build quality and functional grade parts.

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References

1. Jenkins V (2002) Communication from the commission: a sustainable Europe for a better world: a European Union Strategy for sustainable development [Commission's Proposal to the Göteborg European Council]. Journal of Environmental Law 14(2):261–264. https://www.jstor.org/stable/44248370. Accessed 18 Aug 2018
2. Bikas H, Stavropoulos P, Chryssolouris G (2016) Additive manufacturing methods and modeling approaches: a critical review. Int J Adv Manuf Technol 83(1–4):389–405
3. Frazier WE (2014) Metal additive manufacturing: a review. J Mater Eng Perform 23(6):1917–1928
4. Wang X, Xu S, Zhou S, Xu W, Leary M, Choong P, Qian M, Brandt M, Xie YM (2016) Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: a review. Biomaterials 83:127–141
5. Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R (2017) Polymers for 3D printing and customized additive manufacturing. Chem Rev 117(15):10212–10290
6. Costa ECE, Duarte JP, Bártolo P (2017) A review of additive manufacturing for ceramic production. Rapid Prototyp J 23(5):954–963
7. Parandoush P, Lin D (2017) A review on additive manufacturing of polymer-fiber composites. Compos Struct 182:36–53
8. Ferrage L, Bertrand G, Lenormand P, Grossin D, Ben-Nissan B (2017) A review of the additive manufacturing (3DP) of bioceramics: alumina, zirconia (PSZ) and hydroxyapatite. J Aust Ceram Soc 53(1):11–20

9. Hagedorn Y (2017) Laser additive manufacturing of ceramic components: materials, processes, and mechanisms. In Laser Additive Manufacturing (pp. 163–180). Woodhead Publishing. https://www.sciencedirect.com/science/article/pii/B9780081004333000063. Accessed 23 Jan 2018
10. Hammel EC, Ighodaro OLR, Okoli OI (2014) Processing and properties of advanced porous ceramics: an application based review. Ceram Int 40(10):15351–15370
11. Deckers J, Vleugels J, Kruth J-P (2014) Additive manufacturing of ceramics: a review. J Ceram Sci Technol 5(4):245–260
12. Cawley JD (1999) Solid freeform fabrication of ceramics. Curr Opin Solid State Mater Sci 4:483–489, 1999
13. ASTM International (2013) F2792-12a - standard terminology for additive manufacturing technologies (ASTM International, West Conshohocken, PA, 2012). P. Jain, AM Kuthe, Feasibility study of manufacturing using rapid prototyping: FDM approach. Procedia Eng 63:4–11
14. Schwentenwein M, Homa J (2015) Additive manufacturing of dense alumina ceramics. Int J Appl Ceram Technol 12(1):1–7
15. Wang J-C and Dommati H (2018) Fabrication of zirconia ceramic parts by using solvent-based slurry stereolithography and sintering. Int J Adv Manuf Technol 98(5–8):1537–1546
16. Scheithauer U, Schwarzer E, Moritz T, Michaelis A (2018) Additive manufacturing of ceramic heat exchanger: opportunities and limits of the lithography-based ceramic manufacturing (LCM). J Mater Eng Perform 27(1):14–20
17. Mitteramskogler G, Gmeiner R, Felzmann R, Gruber S, Hofstetter C, Stampfl J, Ebert J, Wachter W, Laubersheimer J (2014) Light curing strategies for lithography-based additive manufacturing of customized ceramics. Addit Manuf 1:110–118
18. Snelling DA, Williams CB, Suchicital CTA, Druschitz AP (2017) Binder jetting advanced ceramics for metal-ceramic composite structures. Int J Adv Manuf Technol 92(1–4):531–545
19. Gonzalez JA, Mireles J, Lin Y, Wicker RB (2016) Characterization of ceramic components fabricated using binder jetting additive manufacturing technology. Ceram Int 42(9):10559–10564
20. Curodeau A, Sachs E, Caldarise S (2000) Design and fabrication of cast orthopedic implants with freeform surface textures from 3-D printed ceramic shell. J Biomed Mater Res 53(5):525–535
21. Ainsley C, Reis N, Derby B (2002) Freeform fabrication by controlled droplet deposition of powder filled melts. J Mater Sci 37(15):3155–3161
22. Noguera R, Lejeune M, Chartier T (2005) 3D fine scale ceramic components formed by ink-jet prototyping process. J Eur Ceram Soc 25(12):2055–2059
23. Derby B (2011) Inkjet printing ceramics: from drops to solid. J Eur Ceram Soc 31(14):2543–2550
24. Soltman D, Subramanian V (Mar. 2008) Inkjet-printed line morphologies and temperature control of the coffee ring effect. Langmuir 24(5):2224–2231
25. Scheithauer U, Johne R, Weingarten S, Schwarzer E, Richter HJ, Moritz T, Michaelis A (2018) Investigation of droplet deposition for suspensions usable for thermoplastic 3D printing (T3DP). J Mater Eng Perform 27(1):44–51
26. Wang T, Derby B (2005) Ink-jet printing and sintering of PZT. J Am Ceram Soc 88(8):2053–2058
27. Onagoruwa S, Bose S, and Bandyopadhyay A (2001) Fused deposition of ceramics (FDC) and composites, Proc. Solid Free. Fabr. Symp., no. June, pp. 224–231
28. Vaidyanathan R, Walish J, Lombardi JL, Kasichainula S, Calvert P, Cooper KC (2000) Extrusion freeforming of functional ceramic prototypes. JOM 52(12):34–37
29. Kruth JP, Mercelis P, Van Vaerenbergh J, Froyen L, Rombouts M (2005) Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyp J 11(1):26–36
30. Yap CY, Chua CK, Dong ZL, Liu ZH, Zhang DQ, Loh LE, Sing SL (2015) Review of selective laser melting: materials and applications. Appl Phys Rev vol. 2, no. 4
31. Shahzad K, Deckers J, Kruth JP, Vleugels J (2013) Additive manufacturing of alumina parts by indirect selective laser sintering and post processing. J Mater Process Technol 213(9):1484–1494
32. Tang HH, Chiu ML, Yen HC (2011) Slurry-based selective laser sintering of polymer-coated ceramic powders to fabricate high strength alumina parts. J Eur Ceram Soc 31(8):1383–1388
33. Wilkes J, Hagedorn Y, Meiners W, Wissenbach K (2013) Additive manufacturing of ZrO_2-Al_2O_3 ceramic components by selective laser melting. Rapid Prototyp J 19(1):51–57
34. Wang XH, Fuh JYH, Wong YS, Tang YX (2003) Laser sintering of silica sand - mechanism and application to sand casting mould. Int J Adv Manuf Technol 21(12):1015–1020
35. Liu K, Shi Y, He W, Li C, Wei Q, Liu J (2013) Densification of alumina components via indirect selective laser sintering combined with isostatic pressing. Int J Adv Manuf Technol 67(9–12):2511–2519
36. Liu K, Sun H, Tan Y, Shi Y, Liu J, Zhang S, Huang S (2017) Additive manufacturing of traditional ceramic powder via selective laser sintering with cold isostatic pressing. Int J Adv Manuf Technol 90(1–4):945–952
37. Ho HCH, Gibson I, Cheung WL (1999) Effects of energy density on morphology and properties of selective laser sintered polycarbonate. J Mater Process Technol 89–90:204–210
38. Gabrielsson J, Politis D, Dahlstrand ÅL and Patents A, Article information: users who downloaded this article also downloaded: about Emerald www.emeraldinsight.com Emerald is a global publisher linking research and practice to the benefit of society. The company manages a portfolio of 2014.
39. Klosterman DJ, Chartoff R, Priore B, Osborne N, Graves G, Lightman A, Han G, Pak S, Weaver J (1996) Structural composites via laminated object manufacturing LOM. Solid Free Fabr Symp Proc:105–115
40. Jabbari M, Bulatova R, Tok AIY, Bahl CRH, Mitsoulis E, Hattel JH (2016) Ceramic tape casting: a review of current methods and trends with emphasis on rheological behaviour and flow analysis. Mater Sci Eng B Solid-State Mater Adv Technol 212:39–61
41. Zhang Y, He X, Du S, Zhang J (2001) Al2O3ceramics preparation by LOM (laminated object manufacturing). Int J Adv Manuf Technol 17(7):531–534
42. Horvitz D, Gotman I, Gutmanas EY, Claussen N (2002) In situ processing of dense Al2O3-Ti aluminide interpenetrating phase composites. J Eur Ceram Soc 22(6):947–954
43. Yin X, Travitzky N, Greil P (2007) Near-net-shape fabrication of Ti3AlC2-based composites. Int J Appl Ceram Technol 4(2):184–190
44. Krinitcyn M, Fu Z, Harris J, Kostikov K, Pribytkov GA, Greil P, Travitzky N (2017) Laminated object manufacturing of in-situ synthesized MAX-phase composites. Ceram Int 43(12):9241–9245
45. Windsheimer H, Travitzky N, Hofenauer A, Greil P (2007) Laminated object manufacturing of preceramic-paper-derived Si-SiC composites. Adv Mater 19(24):4515–4519
46. Li Y, Hu Y, Cong W, Zhi L, Guo Z (2017) Additive manufacturing of alumina using laser engineered net shaping: effects of deposition variables. Ceram Int 43(10):7768–7775
47. Yan S, Wu D, Ma G, Niu F, Kang R, Guo D (2017) Formation mechanism and process optimization of nano Al2O3-

ZrO2eutectic ceramic via laser engineered net shaping (LENS). Ceram Int 43(17):14742–14747
48. Niu F, Wu D, Ma G, Wang J, Zhuang J, Jin Z (2016) Rapid fabrication of eutectic ceramic structures by laser engineered net shaping. Procedia CIRP 42 Isem Xviii:91–95
49. Weimer AW (2012) Carbide, nitride and boride materials synthesis and processing. Springer Science & Business Media pp. 16
50. Balla VK, Bose S, Bandyopadhyay A (2008) Processing of bulk alumina ceramics using laser engineered net shaping. Int J Appl Ceram Technol 5(3):234–242
51. Ebert J, Özkol E, Zeichner A, Uibel K, Weiss Ö, Koops U, Telle R, Fischer H (2009) Direct inkjet printing of dental prostheses made of zirconia. J Dent Res 88(7):673–676
52. He R, Liu W, Wu Z, An D, Huang M, Wu H, Jiang Q, Ji X, Wu S, Xie Z (2018) Fabrication of complex-shaped zirconia ceramic parts via a DLP- stereolithography-based 3D printing method. Ceram Int 44(3):3412–3416
53. Zhao HP, Ye CS, Fan ZT, and Shi YN (2016) 3D printing of ZrO2 ceramic using nano-zirconia suspension as a binder, Proc. 2015 4th Int. Conf. Sensors, Meas. Intell. Mater., vol. 43, no. Icsmim 2015, pp. 654–657
54. Corcione CE, Greco A, Montagna F, Licciulli A, Maffezzoli A (2005) Silica moulds built by stereolithography. J Mater Sci 40(18):4899–4904
55. Schwetz KA, Sigl LS, Pfau L (1997) Mechanical properties of injection molded B 4 C – C. Ceramics 76(133):68–76
56. Thornton A (2015) Freeze-form extrusion fabrication of boron carbide Masters Theses. https://scholarsmine.mst.edu/masters_theses/7439/
57. Kluess D, Bergschmidt P, Mittelmeier W, and Bader R (2014) Ceramics for joint replacement, in Joint replacement technology, Elsevier pp. 152–166
58. Kokubo T (1990) Surface chemistry of bioactive glass-ceramics. J Non-Cryst Solids 120(1–3):138–151
59. Neuman EW, Hilmas GE, Fahrenholtz WG (2015) Mechanical behavior of zirconium diboride–silicon carbide–boron carbide ceramics up to 2200 C. J Eur Ceram Soc 35(2):463–476
60. Bal BS, Rahaman MN (2012) Orthopedic applications of silicon nitride ceramics. Acta Biomater 8(8):2889–2898
61. Pittroff W, Erbert G, Beister G, Bugge F, Klein A, Knauer A, Maege J, Ressel P, Sebastian J, Staske R, Traenkle G (2001) Mounting of high power laser diodes on boron nitride heat sinks using an optimized Au/Sn metallurgy. IEEE Trans Adv Packag 24(4):434–441
62. Kelly Patrick M, Francis Rose LR (2002) The martensitic transformation in ceramics — its role in transformation toughening. Prog Mater Sci 47(5):463–557
63. Wu H, Liu W, He R, Wu Z, Jiang Q, Song X, Chen Y, Cheng L, Wu S (2017) Fabrication of dense zirconia-toughened alumina ceramics through a stereolithography-based additive manufacturing. Ceram Int 43(1):968–972
64. Yen HC (2015) Experimental studying on development of slurry-layer casting system for additive manufacturing of ceramics. Int J Adv Manuf Technol 77(5–8):915–925
65. Costakis WJ, Rueschhoff LM, Diaz-Cano AI, Youngblood JP, Trice RW (2016) Additive manufacturing of boron carbide via continuous filament direct ink writing of aqueous ceramic suspensions. J Eur Ceram Soc 36(14):3249–3256
66. Seerden KAM, Reis N, Evans JRG, Grant PS, Halloran JW, Derby B (2001) Ink-jet printing of wax-based alumina suspensions. J Am Ceram Soc 84(11):2514–2520
67. Scheithauer U, Schwarzer E, Richter HJ, Moritz T (2015) Thermoplastic 3D printing - an additive manufacturing method for producing dense ceramics. Int J Appl Ceram Technol 12(1): 26–31
68. Ghazanfari A, Li W, Leu MC, Hilmas GE (2017) A novel freeform extrusion fabrication process for producing solid ceramic components with uniform layered radiation drying. Addit. Manuf. 15:102–112
69. Bengisu M (2013) Engineering ceramics. Springer Science & Business Media
70. Somiya S, Roy R (2000) Hydrothermal synthesis of fine oxide powders. Bull Mater Sci 23(6):453–460
71. Nakonieczny DS, Antonowicz M, Paszenda ZK, Radko T, Drewniak S, Bogacz W, Krawczyk C (2018) Experimental investigation of particle size distribution and morphology of alumina-yttria-ceria-zirconia powders obtained via sol–gel route. Biocybern Biomed Eng 38(3):535–543
72. Chick LA, Pederson LR, Maupin GD, Bates JL, Thomas LE, Exarhos GJ (1990) Glycine-nitrate combustion synthesis of oxide ceramic powders. Mater Lett 10(1–2):6–12
73. Li L et al. (2018) Synthesis of nano-AlN powders from Al wire by arc plasma at atmospheric pressure, Ceram Int 44(17):21810–21815
74. Grida I, Evans JRG (2003) Extrusion freeforming of ceramics through fine nozzles. J Eur Ceram Soc 23(5):629–635
75. Clarke DR, Oechsner M, Padture NP (2012) Thermal-barrier coatings for more efficient gas-turbine engines. MRS Bull 37(10):891–898
76. Hench LL (1991) Bioceramics: from concept to clinic. J Am Ceram Soc 74(7):1487–1510
77. Lusquiños F, del Val J, Arias-González F, Comesaña R, Quintero F, Riveiro A, Boutinguiza M, Jones JR, Hill RG, Pou J (2014) Bioceramic 3D implants produced by laser assisted additive manufacturing. Phys Procedia 56:309–316
78. Inzana JA, Trombetta RP, Schwarz EM, Kates SL, Awad HA (2015) 3D printed bioceramics for dual antibiotic delivery to treat implant-associated bone infection. Eur Cell Mater 30:232–247
79. Parthasarathy J (2014) 3D modeling, custom implants and its future perspectives in craniofacial surgery. Ann Maxillofac Surg 4(1):9–18
80. Rabinskiy LN, Sitnikov SA, Pogodin VA, Ripetskiy AA, Solyaev YO (2017) Binder jetting of Si3N4 ceramics with different porosity. Solid State Phenom 269:37–50
81. Mancuso E, Alharbi N, Bretcanu OA, Marshall M, Birch MA, McCaskie AW, Dalgarno KW (2017) Three-dimensional printing of porous load-bearing bioceramic scaffolds. Proc Inst Mech Eng Part H J Eng Med 231(6):575–585
82. Silva NRFA, Witek L, Coelho PG, Thompson VP, Rekow ED, Smay J (2011) Additive CAD/CAM process for dental prostheses. J Prosthodont Implant Esthet Reconstr Dent 20(2):93–96
83. Dehurtevent M, Robberecht L, Hornez J-C, Thuault A, Deveaux E, Béhin P (2017) Stereolithography: a new method for processing dental ceramics by additive computer-aided manufacturing. Dent Mater 33(5):477–485
84. Syed-Khaja A and Franke J (2016) Selective laser melting for additive manufacturing of high-temperature ceramic circuit carriers, in Electronic Components and Technology Conference (ECTC), 2016 IEEE 66th. pp. 837–842
85. Jones CS, Lu X, Renn M, Stroder M, Shih W-S (2010) Aerosol-jet-printed, high-speed, flexible thin-film transistor made using single-walled carbon nanotube solution. Microelectron Eng 87(3):434–437
86. Sarobol P, Cook A, Clem PG, Keicher D, Hirschfeld D, Hall AC, Bell NS (2016) Additive manufacturing of hybrid circuits. Annu Rev Mater Res 46(1):41–62

87. Padture NP (2016) Advanced structural ceramics in aerospace propulsion. Nat Mater 15(8):804–809
88. Huang T, Mason MS, Zhao X, Hilmas GE, Leu MC (2009) Aqueous-based freeze-form extrusion fabrication of alumina components. Rapid Prototyp J 15(2):88–95