

Preparation of soluble ceramic cores via additive manufacturing technology: A review

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Abstract: Ceramic cores are key components in the production of castings with complex cavity structures. With the continuous development of the aerospace field, the demand for the castings with complex cavity structures is increasing. When using insoluble ceramic cores for casting, there is a significant challenge in removing complex blind cavities, which severely affects the completeness of the shape of the castings. Soluble ceramic cores can disintegrate when placed in water, greatly simplifying the removal process of cores and ensuring the complete formation of castings with complex cavity structures. Additive manufacturing technology, compared to traditional methods for preparing the soluble ceramic cores, does not require molds and can achieve direct forming of complex cores, simplifying the preparation process and reducing production time and costs. Nowadays, various additive manufacturing technologies, such as stereolithography (SL), selective laser sintering (SLS), direct ink writing (DIW), and binder jetting (BJ) technologies, have been successfully applied to the preparation of the ceramic cores. This paper analyzed the advantages and limitations of various additive manufacturing technologies, reviewed the research progress and raw material classifications of soluble ceramic cores prepared by these technologies, and looked forward to the future developments in the preparation of soluble ceramic cores using additive manufacturing technologies.

Keywords: additive manufacturing; soluble ceramic cores; strength; surface roughness

CLC numbers: TG221⁺.2

Document code: A

Article ID: 1672-6421(2025)05-507-12

1 Introduction

With the rapid development of industries, notably aerospace, the demand for castings like engine casings and turbine blades has sharply increased, thereby placing higher performance requirements on these components^[1-3]. These castings typically feature complex cavities and hollow thin-walled structures, along with slender bends and hidden slots, necessitating the use of cores during the casting process^[4-6]. Traditional core forming processes, such as injection molding, isostatic pressing, and gel injection molding, require molds for preparation of the cores, leading to long production cycles and low efficiency^[7, 8]. They also have significant limitations when forming large and complex structural cores.

Additionally, the cores prepared by traditional materials such as Al_2O_3 and SiO_2 need to be removed by mechanical vibration, alkali corrosion, or other methods. These processes are challenging to achieve ideal results on cores within internal bending channels, and the lye can cause surface corrosion on the castings, affecting their quality. This significantly restricts the application of ceramic cores in casting production^[9-13].

To address the issue of difficult core removal, water-soluble cores have been gradually introduced into casting production. The water-soluble cores mainly include water-soluble salt cores and water-soluble ceramic cores^[14, 15]. The water-soluble salt cores can be removed through dissolution, achieving ideal removal effects. However, their low strength and high brittleness limit their applications^[16, 17]. Although the water-soluble ceramic cores, such as CaO-based ceramic cores, have good performance and are easy to remove, CaO is prone to absorbing water and dehydrating, causing significant issues in core preparation and storage. This also restricts the further application of water-soluble CaO ceramic

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Received: 2024-09-30; Revised: 2024-11-17; Accepted: 2024-11-25

cores in casting production. Calcium carbonate (CaCO_3) comes from a wide range of sources and is decomposed into CaO at high temperatures. Ceramic cores prepared using CaCO_3 as raw materials exhibit good collapsibility after sintering, but relatively few research works can be found in related aspects.

In recent years, the rapid development of additive manufacturing technologies has provided new avenues for the preparation of complex cores^[18-21]. Additive manufacturing is an advanced manufacturing method that uses a computer to slice a three-dimensional model of a part and then prints the part by depositing materials layer by layer^[22-24]. Compared to traditional techniques, the additive manufacturing offers numerous advantages such as high customization, short production cycles, and the ability to produce parts with complex geometries^[25-30]. Additive manufacturing technology does not need mold, can realize the direct forming of complex core, simplify the preparation process, reduce the production time and cost^[31-36], these advantages position additive manufacturing technology as increasingly crucial in the field of ceramic core forming technology. Currently, the main additive manufacturing technologies for the core production include: stereolithography^[37], selective laser sintering (SLS)^[38], direct ink writing^[39], and binder jetting^[40] technologies. This is conducive to promoting the application of ceramic cores in casting production.

This review initially introduces various additive manufacturing technologies, then discusses how these technologies are employed in the preparation of ceramic cores. Furthermore, it elaborates on the process of producing soluble ceramic cores using additive manufacturing technology and examines the influence of additive manufacturing process parameters on the microstructure and properties of ceramic cores. Finally, it discusses the existing challenges faced by different additive manufacturing techniques and ceramic materials in the production of soluble ceramic cores.

2 Preparation of ceramic cores via additive manufacturing technology

2.1 Preparation of ceramic cores via stereolithography

Stereolithography technology is an additive manufacturing technique that utilizes the curing of photosensitive resins upon

exposure to specific light sources to create three-dimensional objects through layer-by-layer printing^[41, 42]. The process flow chart of the stereolithography technology is shown in Fig. 1. This technology achieves high precision in part formation and can produce cores with complex structures. It has already been applied to core preparation.

Li et al.^[44] prepared alumina ceramic slurries with a solid content of 80vol.% using three different powder grades: coarse, medium, and fine, and studied the effect of powder grade design on the performance of ceramic cores. The alumina ceramic cores prepared using stereolithography technology are shown in Fig. 2. The results indicated that when the mass ratio of coarse, medium, and fine particles in the ceramic slurry is 2:1:1 and the sintering temperature is 1,600 °C, the resulting alumina ceramic core exhibits an open porosity of 36.4%, a high-temperature deflection thickness of 2.27 mm, and a flexural strength of 50.1 MPa. This study presents a new method for preparing high-porosity ceramic cores with moderate strength and low high-temperature deformation using stereolithography technology.

Using stereolithography technology can rapidly form complex structured ceramic cores, shortening the preparation cycle. However, it still faces challenges such as significant shrinkage and cracking during the sintering of the ceramic cores, high cost of photosensitive resins, low surface accuracy of the cores, and considerable sintering shrinkage. Further research works on slurry formulations and specific debinding and sintering processes are needed to promote the industrial application of stereolithography technology.

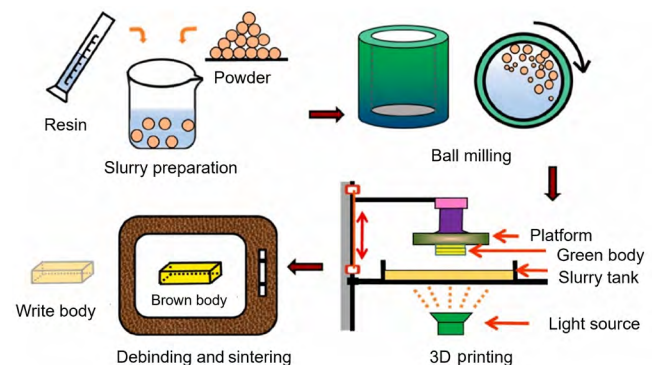


Fig. 1: Schematic diagram of stereolithography technology^[43]

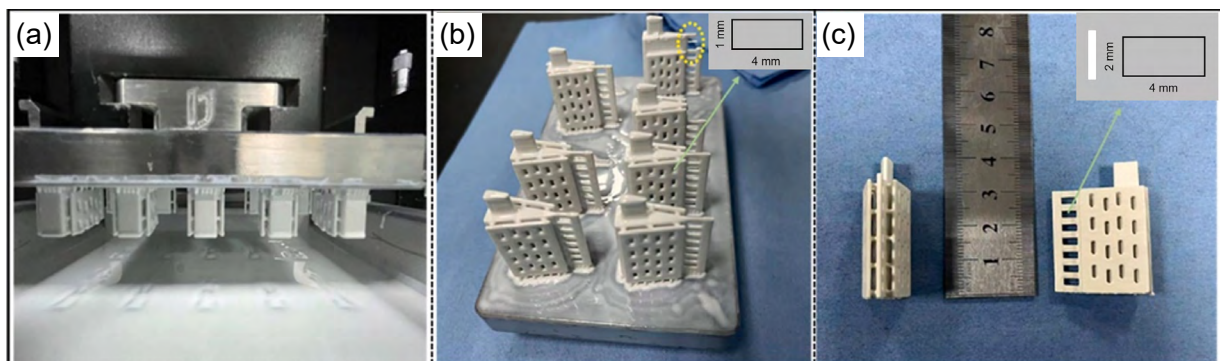


Fig. 2: Ceramic core samples prepared by stereolithography process (a-c)^[45]

2.2 Preparation of ceramic cores via SLS

Selective laser sintering (SLS) is an additive manufacturing technology that uses a high-energy laser beam to selectively sinter powders according to the part's geometry, thereby obtaining the desired part^[46, 47]. The schematic diagram of the SLS technology process is shown in Fig. 3. The SLS technology can address the shortcomings present in traditional core manufacturing techniques, such as limitations of complex shapes, high material waste, and environmental pollution problem, enabling the production of the cores with complex shapes.

The ceramic cores directly prepared by SLS technology have relatively low strength. To enhance their strength, post-processing methods such as sol infiltration and high-temperature sintering are generally employed. Zeng et al.^[48] prepared high-strength, low-shrinkage ceramic cores by infiltrating alumina ceramic core green bodies with nanoscale alumina sol and silica sol. The results showed that after these two infiltration treatments, the pores within the cores were filled with particles from the sol, and mullite reinforcement phases were produced. The porosity of the ceramic cores decreased from 44.7% to 35.3%, and the bending strength increased from 8.2 MPa to 12.6 MPa.

The SLS technology has the advantages of being able to form large and complex structural cores without requiring support structures and having a high utilization rate of raw materials^[49, 50]. However, issues such as high initial investment costs for equipment, difficult maintenance, and low initial strength of the formed green cores limit its wide applications in preparation of cores.

2.3 Preparation of ceramic cores via direct ink writing

The direct ink writing technology is an additive manufacturing technique that uses slurries for part printing. During the printing process, computer software controls the deposition of the slurry at specified locations on the part, followed by layer-by-layer stacking until the part is completed^[51, 52]. Figure 4 illustrates the workflow of direct ink writing technology.

To address the issue of high surface roughness in ceramic cores prepared by direct ink writing technology, Tang et al.^[54] investigated the effects of slurry composition and process parameters on the performance of ceramic cores. The results indicated that the optimal slurry composition was: 50vol.%

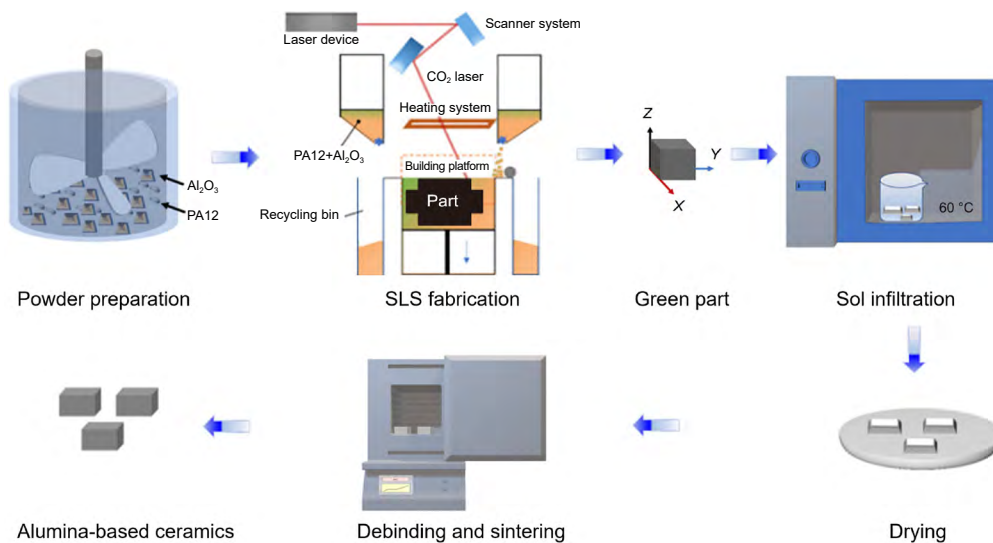


Fig. 3: Schematic diagram showing the process of preparing aluminum-based ceramics by SLS combined with sol infiltration^[46]

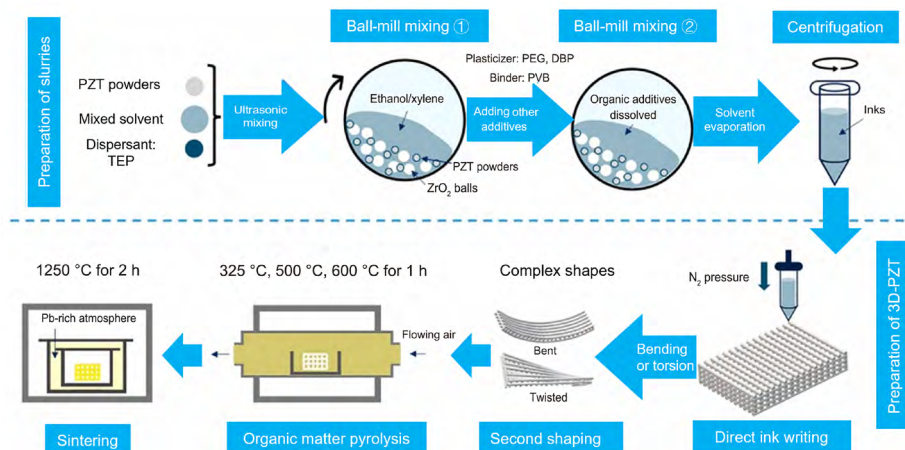


Fig. 4: Schematic diagram of the process of preparing ceramic cores by direct ink writing^[51]

Al_2O_3 , 1.5wt.% acetic acid dispersant, and 2wt.% methyl cellulose aqueous solution. The optimal processing conditions were: printing speed of $15 \text{ mm} \cdot \text{s}^{-1}$, nozzle diameter of 0.40 mm, and a layer height of 70% of the nozzle diameter. Under these optimal conditions, the prepared ceramic cores exhibited uniform structure and a surface roughness of $0.75 \mu\text{m}$, significantly improving the surface quality of the ceramic cores.

The direct ink writing technology does not require external energy sources such as lasers or UV light and can form complex shapes at room temperature. It has low equipment costs and allows for the simultaneous printing of multiple materials. Moreover, the typical high solid content of ceramic slurries results in low drying and sintering shrinkage rates of the ceramic cores. Therefore, the direct ink writing technology is widely used in preparation of ceramic cores.

2.4 Preparation of ceramic cores via binder jetting

The binder jetting technology has developed rapidly in recent years due to its unique advantages. It can automatically slice the three-dimensional model of a part and control the jetting and motion systems of the printer to complete the powder spreading and binder jetting commands, repeating this process until the entire ceramic core is printed^[55-57]. The schematic diagram in Fig. 5 shows the workflow of binder jetting technology. Compared to the aforementioned technologies, the binder jetting technology requires less equipment investment, has a wide range of printing material sources, offers high production efficiency, and does not require support materials when forming large and complex parts, presenting broad prospects for development^[58-60].

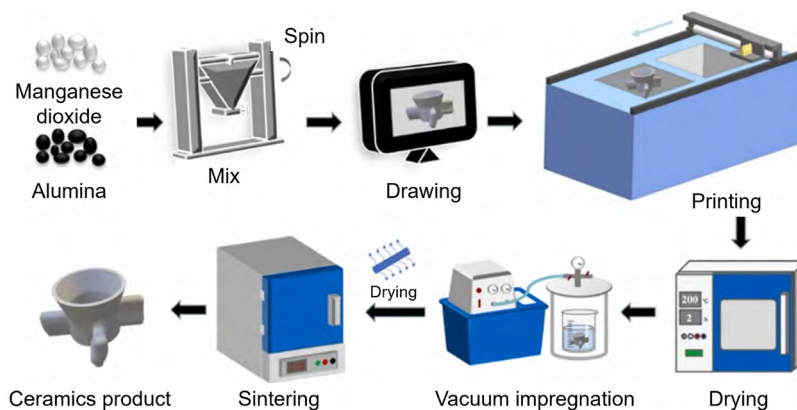


Fig. 5: Diagram of binder jetting technology^[61]

In the binder jetting technology, factors such as powder characteristics, binder, and printing process parameters all influence the strength of green body, microstructure, and the final performance of the formed parts^[60-62]. Researchers have conducted relevant studies on these factors. Yang et al.^[61] added MnO_2 sintering aids to Al_2O_3 powder and vacuum infiltrated the printed green body with TiO_2 sol. After high-temperature sintering, high-performance alumina-based ceramic parts were obtained. Figure 6 shows complex ceramic samples fabricated by binder jetting technology.

During the sintering process, a $\text{MnO-TiO}_2\text{-Al}_2\text{O}_3$ system formed within the ceramics, significantly reduce the sintering temperature. The formation of MnTiO_3 and MnAl_2O_4 in

the system improved the bending strength of the ceramics. Compared with untreated alumina ceramics, the bending strength of alumina ceramics treated with sintering aids and vacuum infiltration increased by 48 times, and the sintered relative density increased by 41.85%^[61].

By adding nanoparticles to the binder or treating the green body with infiltration, it is possible to effectively address the relatively low strength and density of ceramic parts prepared by the binder jetting technology, thus enabling the production of parts with ideal properties and promoting the application of the binder jetting technology in part fabrication.

The additive manufacturing technologies offer high design freedom and can form complex cavity structures. However, the stereolithography technology not only faces issues such as high material and equipment investment costs and difficult maintenance but also produces ceramic cores with significant dimensional shrinkage and poor high-temperature stability, creating many challenges for core-shell matching and high-temperature alloy casting. Similarly, the SLS technology faces problems such as high material and equipment investment costs and difficult maintenance, and the initial green cores formed by SLS technology have low strength, which is unfavorable for subsequent processing.

The direct ink writing technology can form complex shapes at room temperature, has low equipment costs, and can print

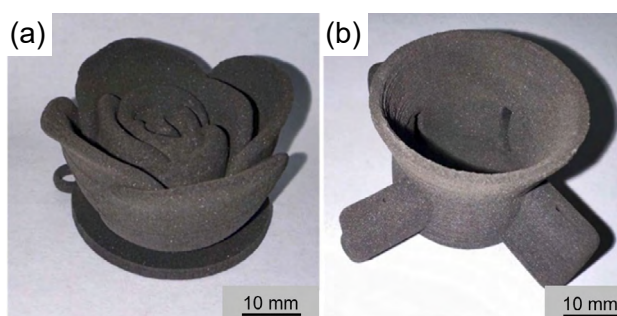


Fig. 6: Complex ceramic samples: (a) rose-shaped; (b) impeller-type shell^[61]

multiple materials simultaneously. Moreover, high-solid-content ceramic slurries can achieve low sintering shrinkage rates of the ceramic cores. Therefore, the direct ink writing technology is suitable for the preparation of the soluble ceramic cores. The binder jetting technology does not require external energy sources such as lasers or UV light, allows for the recycling of unused powders, thus reducing costs and improving manufacturing efficiency. It also eliminates the need for support structures during the forming process and has advantages such as fast forming speed, short forming cycles, and low material costs. Therefore, the binder jetting technology can also be used for the production of complex structured soluble ceramic cores.

3 Preparation of soluble ceramic cores via additive manufacturing technology

3.1 Preparation of soluble ceramic cores via direct ink writing

The direct ink writing technology has the advantages of high production efficiency, the ability to manufacture complex geometrical shapes and hollow structures, lower costs for both the forming equipment and materials, and ease of operation. Different soluble ceramic samples prepared by direct ink writing technology are shown in Fig. 7.

The selection of raw materials for the soluble ceramic cores is crucial. On the one hand, the ceramic cores must possess sufficient strength to withstand the impact of molten metal. On the other hand, the cores must contain soluble substances to ensure their solubility after sintering. Currently, CaO/CaCO_3 is the most common raw material for soluble ceramic cores because CaO -based ceramic cores can achieve a sintered strength of 10–25 MPa, meeting practical casting requirements, and CaO can react directly with water, ensuring good solubility of the ceramic cores [65–68].

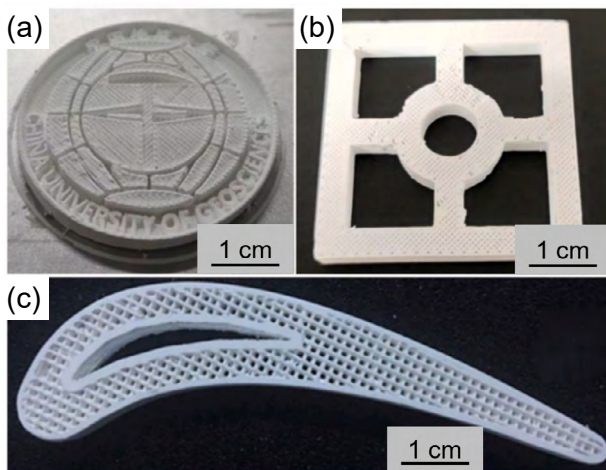


Fig. 7: Different soluble ceramic samples prepared by direct ink writing technology: (a) CUG badge; (b) multi-structured ceramic core; (c) ceramic core with internal porous structure [65]

Scholars have successfully prepared soluble ceramic cores using direct ink writing technology. However, the low surface accuracy of parts formed by direct ink writing technology can affect the surface quality of the casting. To address this issue, Mu et al. [69] used CaCO_3 as the matrix material mixed with polyethylene glycol (PEG) solution to prepare ceramic slurries. They fabricated ceramic green bodies using a direct ink writing apparatus and adopted a stepwise regression method to fit a surface accuracy regression model, studying the effects of needle inner diameter, layer height-to-inner diameter ratio, and printing speed on the accuracy of the ceramic core green bodies, as shown in Fig. 8.

Research results indicate that the needle inner diameter is the primary factor affecting the accuracy of the ceramic core green bodies. The optimal needle inner diameter is 0.41 mm, with a layer height to inner diameter ratio of 0.75 and a printing speed of $29.87 \text{ mm} \cdot \text{s}^{-1}$. Ceramic core green bodies prepared using these process parameters exhibit a surface roughness of $35.39 \mu\text{m}$. The morphology of the 3D-printed ceramic green bodies with optimal process parameters is shown in Fig. 9.

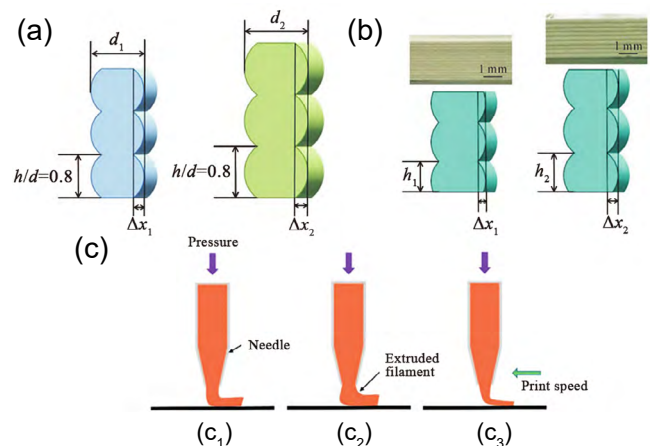


Fig. 8: Modeling the effect of extruded filament build-up on the surface roughness of green bodies with different needle inner diameters ($d_1 < d_2$, $\Delta x_1 < \Delta x_2$) (a); effect of different layer height/inner diameter ratios on the surface morphology of ceramic green bodies ($h_1 < h_2$, $\Delta x_1 < \Delta x_2$) (b); effect of different printing speeds on extruded filaments (c): (c₁) balanced extrusion; (c₂) over extrusion; (c₃) under extrusion [69]

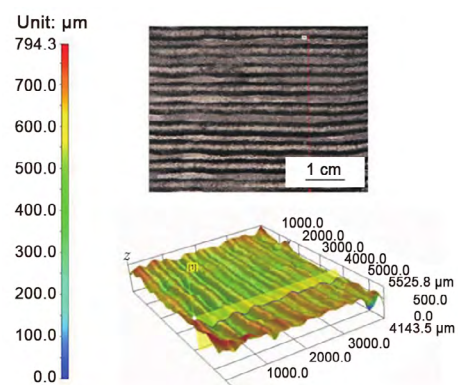


Fig. 9: Surface morphology of the 3D printed ceramic green body obtained with optimal process parameters [69]

To prevent soluble ceramic cores from absorbing moisture and deforming during storage or transportation, Mu et al. [65] added nano-ZrO₂ powder to the CaCO₃ matrix during production of water-resistant soluble ceramic cores using direct ink writing technology. Water-soluble rates of the CaO-based ceramic cores are shown in Fig. 10.

The addition of ZrO₂ enables the formation of CaZrO₃ in the ceramic cores, which does not react with water, thus providing the fabricated ceramic cores with better resistance to hydration. At the same time, CaO remains within the ceramic cores, ensuring their solubility. Figure 11 illustrates mechanism for anti-hydration and water-soluble of the CaO-based ceramic cores [65].

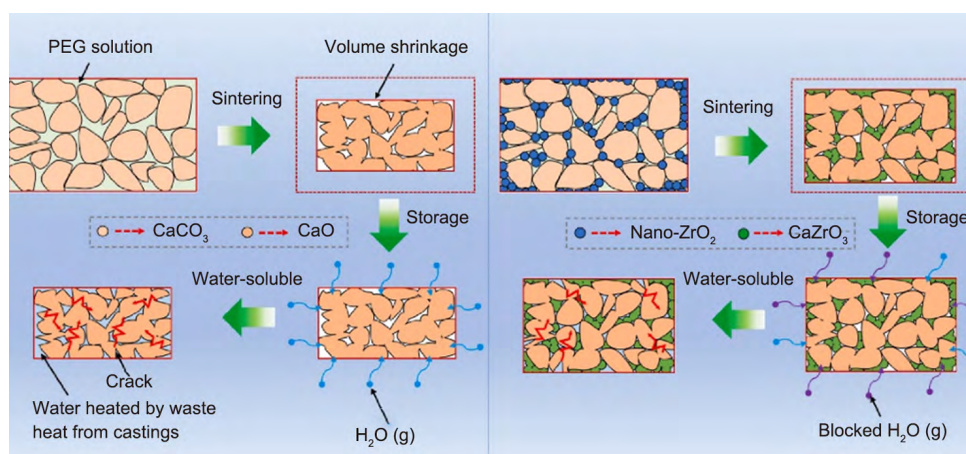


Fig. 11: Mechanism diagram for anti-hydration and water-soluble of the CaO-based ceramic core modified with nano-ZrO₂ [65]

When the addition amount of nano-ZrO₂ powder is 10wt.%, the bending strength of the ceramic core reaches 11.68 MPa, with a shrinkage rate of 16.72%, a 48 h moisture absorption rate of 5.88%, and a water solubility of 4.21 g·s⁻¹·m⁻² at 60 °C [66]. This results in a high-strength, water-resistant soluble ceramic core suitable for the rapid casting of complex parts.

Yang et al. [67] used CaCO₃ and SiO₂ as raw materials to prepare soluble ceramic cores using direct ink writing technology. They studied the effect of the CaO-SiO₂ molar ratio (C/S) on the properties and dispersibility of the green body and sintered samples. The study found that as the C/S ratio increased, the moisture absorption rate of the soluble ceramic cores gradually increased. Change of moisture absorption rate of ceramic cores with storage time after sintered at 1,200 °C for 2 h are presented in Fig. 12 [67].

The study found that when the C/S ratio is low, more Ca₂SiO₄ is present in the sintered core. While, CaO is less abundant, resulting in enhanced strength and resistance to hydration of the core [66]. As the C/S ratio increases, the content of CaO rises. Because CaO is highly hygroscopic, this significantly reduces the water resistance of the soluble ceramic cores. By infiltrating a nano-ZrO₂ dispersion, ZrO₂ reacts with CaO to form CaZrO₃, which is insoluble in water. This reduces the internal CaO content of the ceramic core and can effectively enhance the water resistance of the ceramic cores. The ceramic cores with

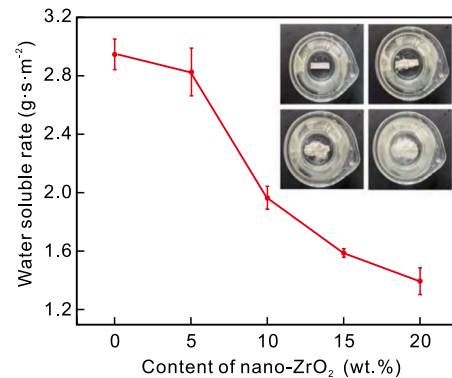


Fig. 10: Water soluble rate of CaO-based ceramic cores with different nano-ZrO₂ contents after sintered at 1,400 °C [65]

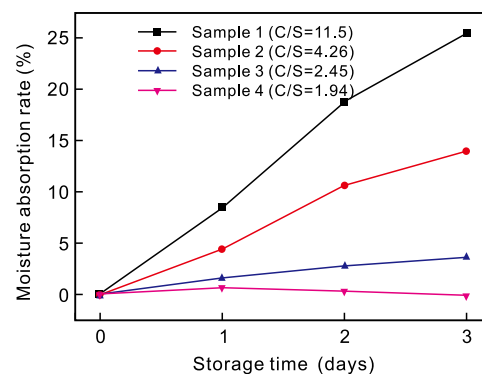


Fig. 12: Moisture absorption rate of ceramic cores sintered at 1,200 °C for 2 h [67]

a C/S ratio of 2.45 exhibit good dispersibility after sintering at 1,200 °C. Moreover, the disintegration rate of the ceramic cores accelerates with an increase in water temperature, making them suitable as alternative cores for aluminum-magnesium alloy castings [65]. The collapsibility of ceramic cores with different C/S ratios after sintering at 1,200 °C for 2 h is shown in the Fig. 13 [67].

Scholars have optimized parameters such as needle inner diameter, layer height-to-inner diameter ratio, and printing speed to address the issue of low surface accuracy in soluble ceramic cores prepared by direct ink writing technology. These

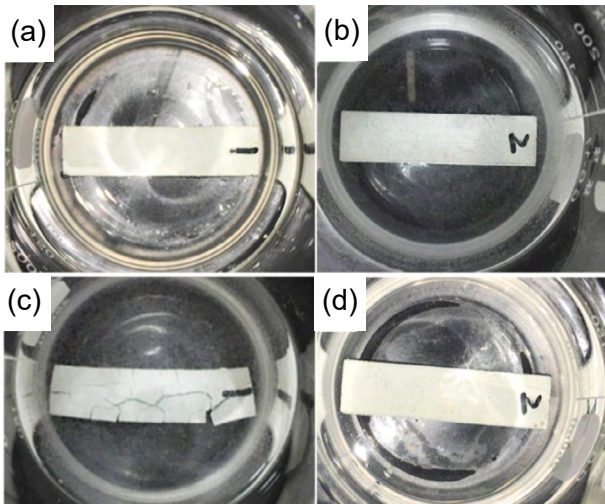


Fig. 13: Collapsibility of ceramic cores sintered at 1,200 °C for 2 h: Sample 1 (C/S=2.45) (a) and Sample 2 (C/S=1.94) (b) at initial moment; Sample 1 (C/S=2.45) (c) and Sample 2 (C/S=1.94) (d) after soaked in water for 110 min ^[67]

optimizations successfully improved the surface accuracy of soluble ceramic cores prepared using direct ink writing to $Ra=35.39\ \mu\text{m}$ ^[69]. To combat the problem of moisture absorption and deformation during storage and transportation, researchers added nano-ZrO₂, SiO₂, and other materials to the CaO/CaCO₃ raw materials. Through a series of reactions during high-temperature sintering, they not only increased the strength of the soluble ceramic cores but also improved their resistance to hydration ^[69]. These advancements promote the industrial application of soluble ceramic cores prepared by additive manufacturing.

3.2 Preparation of soluble ceramic cores via binder jetting

Figure 14 ^[70] shows the soluble ceramic core parts prepared using binder jetting, and their collapsibility is shown in Fig. 15 ^[70].

Fu et al. and Zhao et al. ^[68,71,72] adopted the binder jetting technology, using nano-TiO₂ anhydrous ethanol dispersion and nano-ZrO₂ anhydrous ethanol dispersion as binders respectively, to prepare CaO-based ceramic cores. The study found that CaO can react with nano-TiO₂ and nano-ZrO₂ particles in the binder at high temperatures to produce CaTiO₃ and CaZrO₃. The formation of these substances makes the internal structure of the cores more dense, significantly increasing the flexural strength of the cores. At the same time, CaTiO₃ and CaZrO₃ also enhance the cores' resistance to moisture absorption. The microstructures of CaO-ZrO₂ ceramic core green bodies printed with two different nano-ZrO₂ addition methods are illustrated in Fig. 16 ^[68]. In Figs. 16(a) and (b), the nano-zirconia powder is added in the CaO powder by mechanical mixing. In Fig. 16(c), the same amounts (volumes) of PVP solution and nano-zirconia suspension are sprayed on the powder layer, respectively.

According to Fig. 17 ^[68], at the microscopic level, it can be more clearly observed that with the continuous increase in the content of nano-ZrO₂, the gaps between the ceramics become smaller, and the ceramics become more densely sintered. Nano-ZrO₂ reacts with CaO to form CaZrO₃, which creates tight sinter necks between CaO particles, effectively enhancing the flexural strength and moisture resistance of the soluble ceramic cores.

Although the addition of nano-TiO₂ and nano-ZrO₂ particles improves the moisture resistance of the ceramic cores, CaO raw materials can absorb moisture during storage, transportation,



Fig. 14: Heavy calcium carbonate ceramic core of rotor part by binder jetting: (a) 3D model; (b) green body; (c) sintered part ^[70]



Fig. 15: Images showing the collapse effect of the ceramic core of rotors (a-d) ^[70]

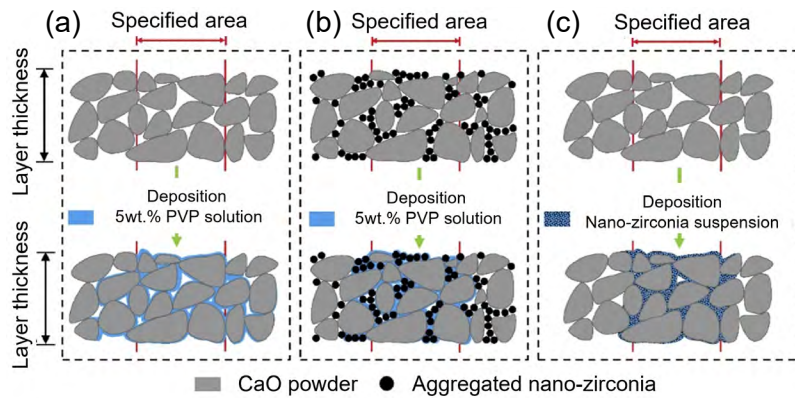


Fig. 16: Schematic diagram of the microstructures of CaO-ZrO₂ ceramic core green bodies printed with the two nano-ZrO₂ addition methods (a-c) ^[68]

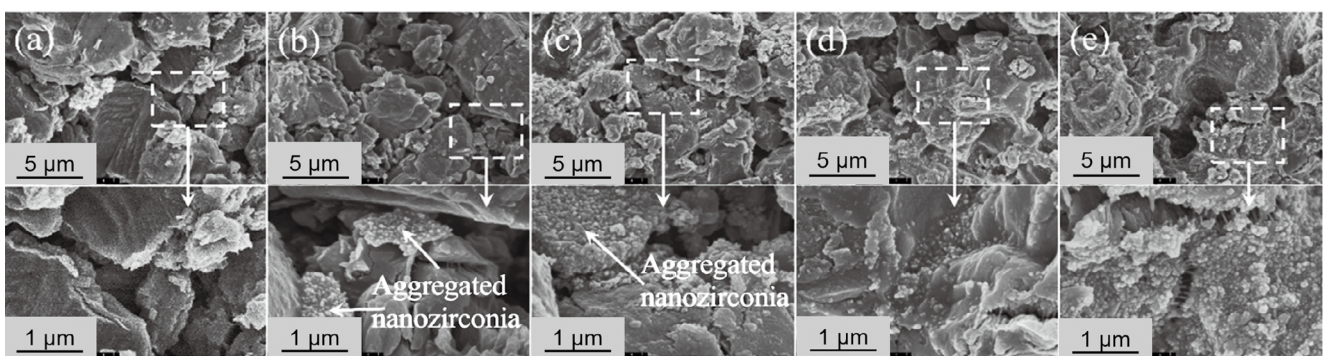


Fig. 17: Microstructures on cross-sections of 3D-printed CaO-based ceramic core green bodies with different precursor materials and binders: (a) CaO powder and 5wt.% PVP solution; (b) CaO powder and 3wt.% nano-ZrO₂ mixed powder and 5wt.% PVP solution; (c) CaO powder and 15wt.% nano-ZrO₂ mixed powder and 5wt.% PVP solution; (d) CaO powder and 4wt.% nano-ZrO₂ suspension; (e) CaO powder and 20wt.% nano-ZrO₂ suspension ^[68]

and preparation, which can lead to difficulties in printing and powder spreading. To address the hygroscopicity issue of CaO, Niu et al. ^[66] used heavy calcium carbonate (HCC) as a raw material and prepared ceramic cores via binder jetting technology. They treated the green body with a nano-ZrO₂ dispersion through vacuum impregnation, obtaining ceramic cores with high strength and good solubility after high-temperature sintering. The dispersion of nano-ZrO₂ into HCC through vacuum impregnation leads to the generation of CaO/MgO upon high-temperature decomposition during sintering. At high temperatures, CaO reacts with nano-ZrO₂ particles to produce CaZrO₃, which can form dense sinter necks among the particles, resulting in ceramic cores with high strength. Figure 18 ^[66] shows the sintering mechanism diagram of the ceramic cores.

Through microstructural analysis presented in Fig. 19 ^[66], it

was observed that after vacuum impregnation with nano-ZrO₂ dispersion, the green body of the soluble ceramic core underwent sintered densely, resulting in a significant reduction in both the number and size of voids. After the vacuum impregnation treatment, as shown in Fig. 19(f), finely dispersed ZrO₂ and CaZrO₃ particles at Point A sinter very tightly with the larger CaO/MgO particles at Point B, effectively enhancing the flexural strength of the ceramic core. Additionally, the outer layer of the soluble ceramic core contains a certain amount of ZrO₂ and CaZrO₃, which acts as a barrier to moisture, ensuring it has good moisture resistance.

After sintering, the ceramic core contains CaO/MgO, both of which can react with water. Therefore, the ceramic cores prepared by this method are soluble in water. The collapse of the HCC ceramic cores is shown in Fig. 20 ^[66].

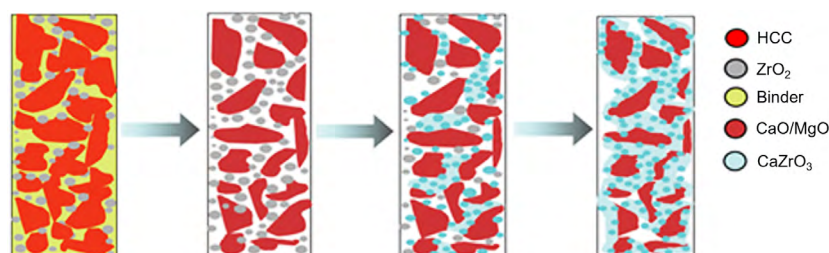


Fig. 18: Sintering mechanism diagram of ceramic cores after vacuum impregnation with nano-ZrO₂ dispersion ^[66]

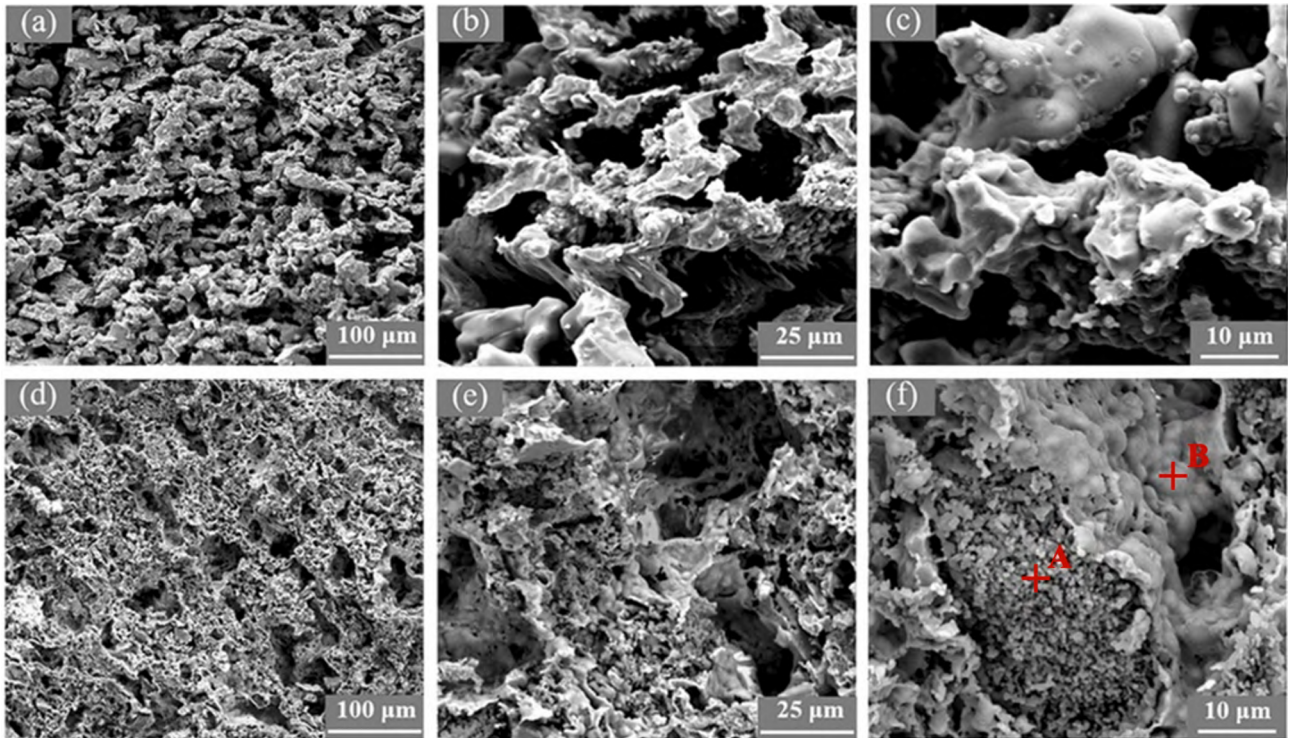


Fig. 19: Microscopic morphologies of the sintered ceramic cores without (a, b, c) and with (d, e, f) vacuum impregnation^[66]

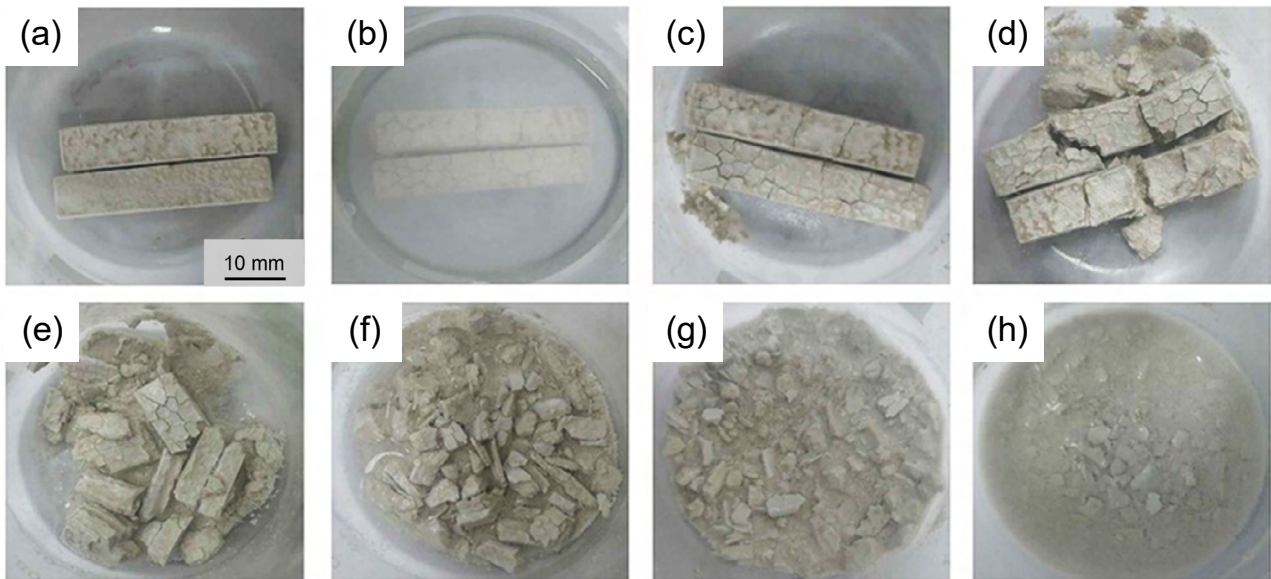


Fig. 20: Collapse of ceramic cores after vacuum impregnation and sintering in hot water for different times: (a) 0 min; (b) 2 min; (c) 5 min; (d) 8 min; (e) 10 min; (f) 15 min; (g) 20 min; (h) 30 min^[66]

Similar to direct ink writing technology, soluble ceramic cores prepared by binder jetting technology also face the issue of moisture absorption and deformation during storage and transportation. To address this problem, researchers have used nano-TiO₂ and nano-ZrO₂ dispersions as inorganic binders or treated the green bodies of CaO/CaCO₃ ceramic cores with nano-ZrO₂ dispersion via vacuum impregnation. These approaches have improved the strength of the soluble ceramic cores and enhanced their resistance to hydration, promoting the industrial application of soluble ceramic cores prepared by additive manufacturing.

4 Summary and future perspectives

The additive manufacturing technologies, due to their short production cycles and high efficiency, as well as the capability to produce complex shapes, have gained widespread application in the aerospace industry. The stereolithography technology, SLS, direct ink writing, and binder jetting technology are among the additive manufacturing technologies that provide important opportunities for the manufacturing of the soluble ceramic cores. These technologies offer advantages such as geometric complexity, customized production, rapid

prototyping, and lower production costs.

However, the stereolithography technology faces issues such as significant shrinkage and cracking during the sintering of the ceramic cores, high cost of photosensitive resins, low surface accuracy of the cores, and considerable sintering shrinkage. The SLS technology faces similar issues like high material and equipment investment costs and difficult maintenance. Furthermore, the initial green bodies formed by SLS technology have low strength, which is unfavorable for subsequent processing. Direct ink writing and binder jetting technologies do not require external energy sources like lasers or UV light. They can form complex shapes at room temperature, and have low equipment and material costs. Scholars have successfully prepared soluble ceramic cores with certain strength, accuracy, and water resistance using stereolithography technology and binder jetting.

The research on preparing the soluble ceramic cores via the additive manufacturing is still in its early stages and faces many challenges which hindering its industrial applications. Firstly, the raw materials used for preparing the soluble ceramic cores via the additive manufacturing are relatively limited, typically using CaO and CaCO₃, where CaO is highly hygroscopic and difficult to store, affecting the forming quality; CaCO₃ decomposes during high-temperature sintering, causing over 20% shrinkage, significantly impacting the dimensional accuracy of the ceramic cores^[66]. Secondly, the surface accuracy of the ceramic cores prepared by the additive manufacturing is low, and there is insufficient related research works. By optimizing the printing layer height, binder saturation, and infiltration treatment, the surface accuracy of the ceramic cores prepared by the binder jetting can reach $Ra=5.70\text{--}7.38\text{ }\mu\text{m}$, whereas the direct ink writing technology can achieve $Ra=35.39\text{ }\mu\text{m}$ with optimal process parameters^[69,73]. In addition, large-sized ceramic cores often develop numerous cracks due to uneven heating during sintering, and the soluble ceramic cores with cracks cannot be used in normal applications^[74]. Therefore, it is necessary to systematically study the sintering process of the ceramic cores. In summary, further research is needed on the surface accuracy and sintering process of the soluble ceramic cores.

The soluble ceramic cores prepared from ceramic powders such as Al₂O₃ and SiO₂ using soluble salts as dry-state binders can effectively solve the issues of hygroscopicity and shrinkage during sintering associated with the CaO/CaCO₃ systems. These soluble ceramic cores have excellent thermal resistance, high strength, and can avoid fracture due to the impact of molten metal, offering broad application prospects^[75, 76]. However, currently, there is limited research on the preparation of soluble ceramic cores from Al₂O₃ and SiO₂ systems using additive manufacturing technologies. Further exploration is needed to investigate the performance and accuracy of these cores. It is hoped that these challenges will be resolved in the near future, paving the way for the industrial application of soluble ceramic cores prepared through additive manufacturing technologies.

Acknowledgment

The authors gratefully acknowledge the supports provided by the National Defense Basic Scientific Research Program (Grant No. JCKY2022213C008).

Conflict of interest

Profs. Zi-tian Fan and Wen-ming Jiang are EBMs of CHINA FOUNDRY. They were not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

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