

引用格式: 张云, 苏海军, 李翔, 等. 耐高温陶瓷基复合材料增材制造技术研究进展[J]. 航空材料学报, 2026, 46(1): 1-14.  
ZHANG Yun, SU Haijun, LI Xiang, et al. Research progress of additive manufacturing technologies for high-temperature resistant ceramic matrix composites[J]. Journal of Aeronautical Materials, 2026, 46(1): 1-14.

## 耐高温陶瓷基复合材料增材制造技术研究进展

张云, 苏海军\*, 李翔, 董栋, 李兴辉, 郭一诺, 申仲琳

(西北工业大学凝固技术全国重点实验室, 西安 710072)

**摘要:** 耐高温陶瓷基复合材料(HT-CMCs)因其卓越的耐高温、高强度、低密度及良好化学稳定性, 在航空航天、能源等极端工况领域应用前景广阔。传统制造工艺在制备复杂形状与高性能 HT-CMCs 时存在局限, 而增材制造(AM)技术以逐层堆积成形的独特优势, 为复杂结构 HT-CMCs 制造开辟了新路径。该技术凭借直接制造冷却通道等复杂内部构型的能力, 显著提升了材料的功能特性及结构效率, 并基于服役需求能够实现性能导向的精准调控与定制化生产, 同时大幅减少材料损耗, 有效降低了制造成本。本文聚焦于 HT-CMCs 增材制造技术, 介绍了其技术原理及应用现状, 重点阐述了 HT-CMCs 材料增材制造体系设计、成形技术、工艺优化等方面的国内外最新研究进展。此外, 本文展望增材制造 HT-CMCs 未来趋势: 材料与工艺协同上, 突破多材料打印界面瓶颈, 开发复合工艺以实现多功能一体化与梯度结构; 智能化体系构建上, 建“数字控制-实时监测-参数优化”系统, 借 AI 调控参数降低试错成本; 模块化与循环制造上, 开发可切换标准化模块, 创新陶瓷废料回收以提高材料利用率, 旨在推动其前沿工程化应用。

**关键词:** 耐高温陶瓷基复合材料; 增材制造; 材料性能; 工艺优化

doi: 10.11868/j.issn.1005-5053.2025.000122

CSTR: 32420.14.j.issn.1005-5053.2025.000122

中图分类号: V254.2

文献标识码: A

文章编号: 1005-5053(2026)01-0001-14

### Research progress of additive manufacturing technologies for high-temperature resistant ceramic matrix composites

ZHANG Yun, SU Haijun\*, LI Xiang, DONG Dong, LI Xinghui, GUO Yinuo, SHEN Zhonglin

(State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072, China)

**Abstract:** High-temperature resistant ceramic matrix composites (HT-CMCs) have demonstrated immense application potential in aerospace, energy, and other extreme service environments, thanks to their outstanding attributes such as exceptional high-temperature resistance, high strength, low density, and excellent chemical stability. Traditional manufacturing processes are constrained in fabricating HT-CMCs with complex shapes and high performance. In contrast, additive manufacturing (AM) technology has paved a new way for the production of HT-CMCs with intricate structures, leveraging its unique capability of layer-by-layer construction. This technology substantially improves the functional properties and structural efficiency of materials by enabling the direct fabrication of complex internal features, like cooling channels. It also supports performance-oriented precise control and customized production according to specific service requirements, while significantly reducing material waste and effectively cutting down manufacturing costs. This paper focuses on the additive manufacturing technology of HT-CMCs. It introduces the technical principles and current application status of this technology, and places particular emphasis on expounding the latest research advancements both domestically and internationally in material system design, forming technologies, and process optimization for additively manufactured HT-CMCs. Furthermore, this paper sets out the future trends of additive manufacturing for HT-CMCs. In terms of material-process synergy, the focus is on overcoming the bottleneck of interface bonding in multi-material printing and developing composite processes to achieve multi-functional integration and gradient structures. Regarding the

construction of intelligent systems, the aim is to establish a “digital control-real-time monitoring-parameter optimization” system and reduce trial-and-error costs through AI-based parameter adjustment. In the realm of modularization and circular manufacturing, the emphasis is on developing interchangeable standardized modules and innovating ceramic waste recycling technologies to enhance material utilization rates. All these endeavors are aimed at promoting its engineering application in cutting-edge fields.

**Key words:** high-temperature resistant ceramic matrix composites (HT-CMCs); additive manufacturing (AM); material property; process optimization

作为先进材料体系,耐高温陶瓷基复合材料 (high-temperature resistant ceramic matrix composites, HT-CMCs) 通过将高熔点、高硬度的陶瓷基体与优良韧性的增强相有机结合,展现出卓越的耐高温性能<sup>[1]</sup>。在高温服役环境下 ( $> 600\text{ }^{\circ}\text{C}$ ), 该类材料不仅具有良好的力学性能与化学稳定性, 而且密度低于传统高温合金<sup>[2-3]</sup>, 因此, 在航空发动机涡轮叶片<sup>[4]</sup>、燃烧室火焰筒<sup>[5]</sup>、发电系统的高温换热器<sup>[6]</sup> 以及核反应堆堆芯结构件<sup>[7]</sup> 等材料性能要求极高的热端部件上, HT-CMCs 都表现出巨大的应用潜力。在制备复杂结构的 HT-CMCs 构件时, 传统制造工艺如化学气相渗透<sup>[8]</sup> (chemical vapor infiltration, CVI)、热压成形<sup>[9]</sup> (hot pressing, HP) 等面临诸多窘境。CVI 工艺制备周期通常较长, 且在材料孔隙率的精准调控方面存在难度 (孔隙率控制精度受温度场均匀性、气体扩散速率等因素影响)。HP 工艺则受限于模具设计, 在复杂构件一体化成形时存在技术瓶颈且原材料利用率低。

增材制造 (additive manufacturing, AM) 作为一种以数字化驱动、基于逐层堆积原理构建三维实体的新型制造模式, 为 HT-CMCs 的制备开辟出新路径<sup>[10]</sup>。HT-CMCs 主要基于粉末床熔融<sup>[11]</sup> (powder bed fusion, PBF)、材料挤出<sup>[12]</sup> (material extrusion, ME)、光固化<sup>[13]</sup> (vat photopolymerization, VPP) 等

核心技术, 直接精准成形出复杂结构 (如蜂窝状冷却通道<sup>[14]</sup>、负泊松比点阵结构<sup>[15]</sup> 等), 在提升构件传热效率的同时结构显著减重。此外, AM 明显的近净成形特性将大幅提升材料利用率, 有效降低制造成本<sup>[16]</sup>。基于此, 本文系统介绍主流 HT-CMCs 增材制造技术的基本原理与工艺特性, 探究不同增材制造方式在 HT-CMCs 中的应用现状, 剖析材料体系、成形技术、工艺优化和性能之间相互影响的内在关系。最后对未来耐高温陶瓷增材制造技术的发展方向进行展望, 旨在为推动该领域的技术创新提供理论支撑与实践指导。

## 1 耐高温陶瓷基复合材料概述

HT-CMCs 由陶瓷基体、增韧材料与界面相构成<sup>[3,17-18]</sup>。陶瓷基体起支撑作用, 传递外部载荷并赋予复合材料耐高温、抗腐蚀等特性; 增韧材料提升材料的强度与韧性, 抑制基体裂纹扩展; 界面相则通过诱导裂纹偏转等机制消耗能量以增强材料的抗破坏能力。作者检索科学引文索引数据库 (SCI) 从 2006 至 2025 年 6 月份的相关数据, 见图 1。在 SCI 数据库中标题含有 “high-temperature resistant ceramic matrix composites” 的论文数量 2006 年 203 篇, 到 2024 年达 1351 篇 (图 1(a)), 这表明近 10 年

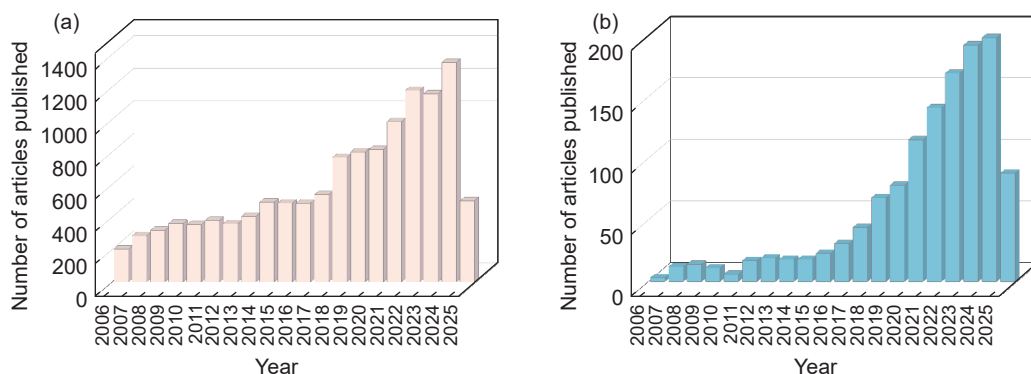


图 1 过去 20 年来每年发表的 SCI 论文标题含有 “high-temperature resistant ceramic matrix composites” (a) 和 “additive manufacturing+ ceramic matrix composites” (b) 的数量

Fig. 1 Annual number of SCI-indexed papers published in the past two decades with titles containing “high - temperature resistant ceramic matrix composites” (a) and “additive manufacturing+ ceramic matrix composites” (b)

间该领域处于技术迭代与应用拓展迅速的阶段。

### 1.1 陶瓷基体

HT-CMCs 基体主要包括氧化物和非氧化物两

种体系,基体材料物化性质差异决定了其应用环境。表 1 是各类耐高温陶瓷基体材料性能及应用对比情况<sup>[19-21]</sup>。

表 1 各类耐高温陶瓷基体材料性能及应用对比<sup>[19-21]</sup>  
Table 1 Comparison of properties and applications of various HT-CMCs<sup>[19-21]</sup>

Materials	Representative systems	Temperature limit/°C	Characteristics	Application scenarios
Alumina-based ceramics	Al <sub>2</sub> O <sub>3</sub> , Al <sub>2</sub> O <sub>3</sub> f/Al <sub>2</sub> O <sub>3</sub>	600-1400	Abundant raw materials; low cost; maintains high hardness and chemical stability at 600-1200 °C	High-temperature furnace linings; glass-forming molds; aerospace structural components
Zirconia-based ceramics	ZrO <sub>2</sub> , ZrO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> composites	800-1200	Phase transformation toughening enhances fracture toughness; Al <sub>2</sub> O <sub>3</sub> addition inhibits microcrack propagation and improves high-temperature strength	High-temperature cutting tools; thermal sensors; refractories; biomedical implants
Carbide ceramics	SiC, ZrB <sub>2</sub> , B <sub>4</sub> C	1600-2600	High thermal conductivity; low thermal expansion; ablation resistance	Hypersonic vehicle leading edges; nuclear cladding
Nitride ceramics	Si <sub>3</sub> N <sub>4</sub> , AlN	1400-1800	High fracture toughness (6-8 MPa·m <sup>1/2</sup> ); excellent thermal shock resistance	Gas turbine blades; high-temperature bearings
Boride ceramics	ZrB <sub>2</sub> -SiC composites	2000-2200	Oxidation/ablation resistance; >90% high-temperature strength retention	Rocket engine nozzles; re-entry capsule thermal protection
High-entropy ceramics	(Hf, Ta, Zr, W)C	3600	Exceptional oxidation resistance; high phase stability	Ultra-high-temperature propulsion systems

#### 1.1.1 氧化物陶瓷基体

氧化物陶瓷基体中, Al<sub>2</sub>O<sub>3</sub> 因原料储量丰富、制备成本低廉,在 600~1200 °C 内具有较高的硬度与化学稳定性,广泛应用于冶金工业的高温炉衬、玻璃制造的成形模具等领域<sup>[22]</sup>。Jiang 等<sup>[23]</sup>通过浆料渗透工艺制成 Al<sub>2</sub>O<sub>3</sub> 纤维增强 Al<sub>2</sub>O<sub>3</sub> 陶瓷基体复合材料,其密度为 (2.95±0.02) g/cm<sup>3</sup>,从室温至 1100 °C 内抗弯强度保持在 (400±8) MPa。Wu 等<sup>[24]</sup>在不锈钢表面制备 Ni<sub>2</sub>Al<sub>3</sub> 涂层,经过 6757 h 的高温服役实验后涂层表面形成以 Al<sub>2</sub>O<sub>3</sub> 相为主的致密抗腐蚀保护层。ZrO<sub>2</sub> 陶瓷则因四方-单斜相转变引发的体积膨胀效应,能够提升断裂韧性,在航空发动机热障涂层领域发挥关键作用<sup>[25]</sup>。任会兰等<sup>[26]</sup>研究表明添加 ZrO<sub>2</sub> 可细化基体 Al<sub>2</sub>O<sub>3</sub> 晶粒,复合陶瓷断裂韧性提升至 8.42 MPa·m<sup>1/2</sup>。

#### 1.1.2 非氧化物陶瓷基体

非氧化物陶瓷基体主要由金属碳化物、硼化物、氮化物和硅化物等材料构成,其原子间主要通过强共价键相连<sup>[27]</sup>,赋予材料超高硬度、出色的高温强度及良好的耐腐蚀性等优良特性。与氧化物陶瓷相比,非氧化物陶瓷更耐高温,在超过 1000 °C 的高温环境依然保持稳定的力学性能。基于此,非氧化物陶瓷成为航空发动机、核反应堆等极端工况

下的理想材料选择<sup>[28-29]</sup>。Lamon 等<sup>[30]</sup>通过化学气相渗透法制备 SiC 基复合材料,在室温至 1600 °C 的高低循环测试中,强度保持率达 90%。Xu 等<sup>[31]</sup>采用高压烧结制备 B<sub>4</sub>C 陶瓷,使塑性变形温度降低 200 °C (与传统烧结样品相比),该材料的抗弯强度在 1300~1600 °C 从 580 MPa 增至 821 MPa。Cai 等<sup>[32]</sup>制备的 C<sub>f</sub>/(Ti<sub>0.2</sub>Zr<sub>0.2</sub>Hf<sub>0.2</sub>Nb<sub>0.2</sub>Ta<sub>0.2</sub>)C-SiC 复合材料在 5 MW/m<sup>2</sup> 热流密度(温度约 2430 °C)下经空气等离子烧蚀考核 300 s,线烧蚀率仅为 2.89 μm/s,展现出非氧化物陶瓷在极端烧蚀环境下的卓越性能。

### 1.2 增韧材料

#### 1.2.1 颗粒增韧

颗粒增韧是将高硬度、高强度的颗粒均匀分散于基体材料中,借助其起到弥散强化<sup>[33]</sup>及对裂纹钉扎等<sup>[34]</sup>作用实现进一步提升材料性能,一般选用 TiC、B<sub>4</sub>C、TiB<sub>2</sub> 和 SiC 等作为颗粒增韧材料。图 2(a)展示了陶瓷基复合材料颗粒增韧的过程<sup>[35]</sup>。Peng 等<sup>[36]</sup>利用 SiC 颗粒增强 (NbTaZrW)C,当 SiC 含量为 50%(体积分数)时,复合材料显微硬度达 22 GPa、抗弯强度 455 MPa、断裂韧性 6.54 MPa·m<sup>1/2</sup>。颗粒增韧体系主要应用于耐高温陶瓷的脆性与热应力问题不突出的小尺寸、结构筒易的构件。但大尺寸构件,需材料满足更高的韧性

与可靠性标准,单纯运用颗粒增韧技术很难解决构件开裂等问题。

### 1.2.2 晶须增韧

晶须增韧是利用晶须的高长径比、高强度及高模量,通过桥联效应等机制来抑制裂纹的扩展<sup>[37]</sup>。图2(b)展示了陶瓷基复合材料晶须增韧的过程<sup>[38]</sup>,常用的晶须材料包括SiC、TiC、Al<sub>2</sub>O<sub>3</sub>、TiO<sub>2</sub>、Si<sub>3</sub>N<sub>4</sub>等。Gu等<sup>[39]</sup>采用化学气相沉积(CVD)技术在C/C复合材料上制备不同微观结构的ZrC晶须增韧ZrC涂层。结果表明,与纯ZrC涂层相比,复合涂层的线性烧蚀率(0.233 μm/s)降低了58.91%。Guo等<sup>[40]</sup>采用机械合金化和放电等离子烧结制备致密SiC<sub>w</sub>/SiAlCN陶瓷,1500℃下等温氧化50h再进行50次热循环后,其抗弯强度依旧保持在449.7 MPa。晶须的增韧效果与其几何形态及物理性能密切相关,针状、棒状结构的增韧效果最为显著,而球状晶须的增韧作用相对较弱。相较于颗粒增韧,晶须对耐高温陶瓷基复合材料的强韧化效果更加突出。

### 1.2.3 纤维增韧

纤维增韧是利用纤维的载荷传递和裂纹偏转机制实现有效克服陶瓷脆性。当前,高温纤维增韧体系主要有碳纤维、碳化硅纤维和氧化物纤维三类<sup>[41]</sup>。图2(c)展示了陶瓷基复合材料纤维增韧的过程<sup>[42]</sup>。碳纤维具有高比强度与低密度,适用于航空航天、能源、交通等领域。Guo等<sup>[43]</sup>提出反应熔体渗透快速制备致密碳纤维增强(TiZrHfNbTa)C

高熵陶瓷复合材料,其表现出优异的抗弯强度(612.6 MPa)和低烧蚀速率。Chen等<sup>[44]</sup>采用ZrSi<sub>2</sub>合金熔渗多孔C/C-B<sub>4</sub>C预制体,成功制备出C/SiC-ZrC-ZrB<sub>2</sub>复合材料。该材料在2100℃等离子烧蚀300s后,线烧蚀率低,仅为0.58 μm/s,质量损失率仅0.8 mg/(cm<sup>2</sup>·s)。此外,碳化硅纤维在高温(1200℃)惰性环境中具有优异的高温性能和化学稳定性。基于此,Matovic等<sup>[45]</sup>利用碳化硅纤维增强碳化硼陶瓷基体,采用场辅助烧结技术制备B<sub>4</sub>C-SiC<sub>f</sub>复合材料。SiC含量为5%时,复合材料致密度高达99%,线性烧蚀速率为13.3 μm/s(1800℃)。氧化物纤维,如Al<sub>2</sub>O<sub>3</sub>纤维和ZrO<sub>2</sub>纤维,在航空航天、能源、环保等领域有着重要应用。Jiang等<sup>[23]</sup>通过浆料渗透工艺制备Al<sub>2</sub>O<sub>3</sub>纤维增强Al<sub>2</sub>O<sub>3</sub>陶瓷基复合材料,经受热震实验(在1100℃)后,复合材料的微观结构和抗弯强度均保持稳定。Zhang等<sup>[46]</sup>以氧化锆纤维为增强相制备ZrO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>气凝胶,材料表现出优异的热稳定性和隔热性能。此外,高熵陶瓷纤维增韧体系由多种金属元素与碳、氮、氧等非金属元素组成,具有独特的物理和化学性能。在超高温环境下在等离子烧蚀过程中展现出卓越的抗氧化能力<sup>[47]</sup>。纤维增韧的目的是改善陶瓷材料固有的脆性、提升复合材料韧性。借助裂纹偏转、纤维桥接及纤维拔出等机制,可显著增韧。在各类纤维中,连续碳纤维增韧效果尤为突出,应用也最广泛。但存在难以完全致密化的问题,需与其他多种制备方法结合使用。

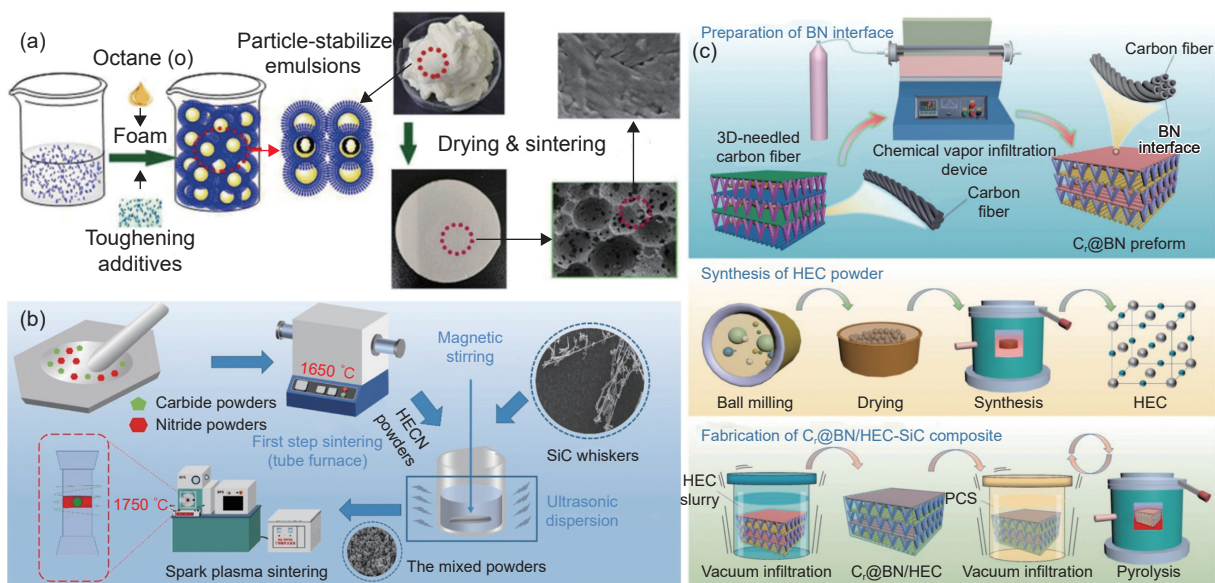


图2 陶瓷基复合材料增韧过程 (a)颗粒增韧<sup>[35]</sup>; (b)晶须增韧的过程<sup>[38]</sup>; (c)纤维增韧<sup>[42]</sup>

Fig. 2 Toughening processes of ceramic matrix composites (a) particle toughening<sup>[35]</sup>; (b) whisker toughening process<sup>[38]</sup>; (c) fiber toughening<sup>[42]</sup>

### 1.3 界面相

在耐高温陶瓷基复合材料(HT-CMCs)中,界面相作为增强相与陶瓷基体间的关键过渡材料,其微观结构和性能对复合材料的力学行为及高温可靠性起着决定性作用,其主要起到应力传递、裂纹调控以及热匹配协调作用<sup>[48]</sup>。界面相的常见类型有氧化物(如  $\text{Al}_2\text{O}_3$ 、 $\text{Y}_2\text{O}_3$ )、非氧化物(BN、SiC、PyC)和梯度复合(SiC/BN)。界面相调控与性能优化可从微观结构设计和界面相功能化入手。Qiu等<sup>[49]</sup>在SiC纤维预制体表面制备PyC/BN多相界面相,再通过聚合物浸渍热解(PIP)工艺获得SiC纤维增强SiC陶瓷基复合材料。结果表明,PyC界面相和BN界面相的厚度分别为20  $\mu\text{m}$ 和30  $\mu\text{m}$ 时,复合材料的抗弯强度和断裂韧度分别达到660.65 MPa和29.01  $\text{MPa}\cdot\text{m}^{1/2}$ 。然而,现阶段界面相在极端环境适应性、复杂载荷匹配性及规模化生产等方面仍面临挑战。

## 2 HT-CMCs 增材制造技术原理与挑战

目前,增材制造技术已在多个领域实现应用。而增材制造陶瓷基复合材料既具备材料本身的高性能优势,又能发挥增材技术的设计灵活性,成为该领域备受关注的研究方向。从学术研究热度来看(图1(b)),在科学引文索引数据库(SCI)中标题包含“additive manufacturing+ceramic matrix composites”的论文,2006年发表数量仅为3篇,到2024年高达198篇。这说明陶瓷基复合材料的增材制造技术在学术研究层面热度持续攀升。论文发表数量的持续增加既反映出该技术的关注度,也暗示其背后存在亟待解决的复杂问题。本章节旨在从共性技术原理框架入手,对应用于HT-CMCs的增材制造核心问题进行系统归纳与分析。

### 2.1 HT-CMCs 增材制造技术原理

当前应用于HT-CMCs的增材制造技术主要基于四大类原理,其核心在于如何按数字模型逐层选择性地固化或粘接陶瓷材料(包括粉末、浆料或丝材):

(1)激光热致相变类(粉末床熔融, powder bed fusion, PBF):利用高能激光束选择性烧结或熔融预先铺平的陶瓷粉末床<sup>[50-51]</sup>。激光束根据切片数据在粉末层表面精确扫描,使指定区域的粉末颗粒烧结黏结(选择性激光烧结, selective laser sintering, SLS, 图3(a)<sup>[52]</sup>)或熔融结合(选择性激光熔化, selective laser melting, SLM, 图3(b)<sup>[53]</sup>),未熔区域粉末作为支撑。一层完成后,铺覆新粉层并重复该过

程。其优势在于成形精度高、可制造复杂内腔结构。

(2)挤出凝固类(材料挤出, material extrusion, ME):通过喷嘴连续挤出热塑性丝材(含陶瓷填料)或陶瓷基的膏体(高固含量浆料)<sup>[54-55]</sup>。挤出的材料按预设路径沉积在构建平台上,并依靠即时冷却/固化(熔融沉积, fused deposition modeling, FDM, 图3(c)<sup>[56]</sup>)或自身流变性(直接墨水书写, direct ink writing, DIW, 图3(d)<sup>[57]</sup>)保持形状,逐层堆积成形。该技术设备成本相对较低,适合结构相对简单的部件和小批量生产。

(3)光聚合固化类(光固化, vat photopolymerization, VPP):利用特定波长光源(紫外光)选择性固化含有陶瓷颗粒的光敏树脂浆料<sup>[58]</sup>。光源(点光源: stereolithography, SLA, 图3(e)<sup>[59]</sup>;面光源: digital light processing, DLP, 图3(f)<sup>[60]</sup>)根据切片数据图案化照射浆料表面,引发光聚合反应使浆料固化成形。一层固化后,平台移动使新浆料覆盖表面进行下一层固化,此技术能实现极高的成形精度和优异的表面粗糙度。

(4)喷射黏结类(喷射技术, jetting):该类技术通过喷头选择性喷射液态材料实现逐层成形,其核心在于利用喷射的微滴精确黏结材料单元<sup>[61-62]</sup>。主要包括黏合剂喷射(binder jetting, BJ, 原理示意图<sup>[63]</sup>见图3(g))及材料喷射(material jetting, MJ, 原理示意图<sup>[64]</sup>见图3(h))。该类技术成形速度快、材料适应性广,为实现多材料打印和功能梯度材料制造提供可能。

上述各类技术虽实现路径各异,但均遵循“离散-堆积”的增材制造基本原理,理解这些共性原理是深入剖析HT-CMCs增材制造所面临独特挑战的基础。

## 2.2 HT-CMCs 增材制造技术核心问题与挑战

### 2.2.1 材料体系设计瓶颈

HT-CMCs增材制造对材料的“可打印性”与“性能”提出双重要求。无论是PBF技术所需的HT-CMCs粉末,还是ME所用的墨水,其物理化学性质直接决定工艺稳定性。PBF技术要求粉末粒径分布合适、流动性良好和团聚性低,但HT-CMCs粉末硬度高导致在制备过程中易引入杂质,超细粉末也易因范德华力而团聚,影响铺粉均匀性<sup>[65]</sup>;对于DIW等挤出技术,HT-CMCs墨水需同时满足较高的固相含量与适宜的流变特性,而黏结剂的引入又会导致后续脱脂过程产生体积收缩,引发开裂<sup>[66]</sup>。此外,HT-CMCs增材制造的目标是制备“近净成形”的高性能构件,但材料设计常陷入两

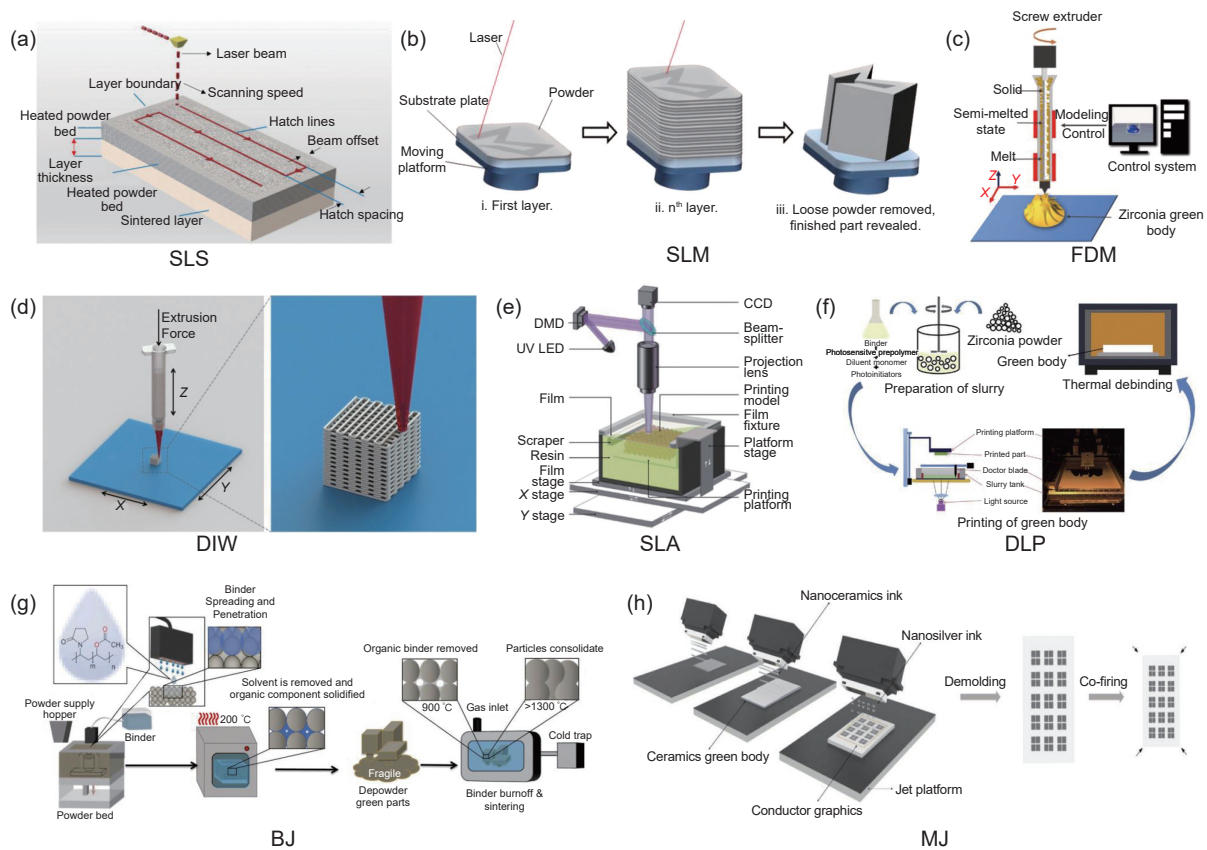


图 3 不同种类陶瓷增材制造原理示意图 (a)SLS<sup>[52]</sup>; (b)SLM<sup>[53]</sup>; (c)FDM<sup>[56]</sup>; (d)DIW<sup>[57]</sup>; (e)SLA<sup>[59]</sup>; (f)DLP<sup>[60]</sup>; (g)BJ<sup>[63]</sup>; (h)MJ<sup>[64]</sup>

Fig. 3 Schematic diagrams of different ceramic additive manufacturing technologies (a) SLS<sup>[52]</sup>; (b) SLM<sup>[53]</sup>; (c) FDM<sup>[56]</sup>; (d) DIW<sup>[57]</sup>; (e) SLA<sup>[59]</sup>; (f) DLP<sup>[60]</sup>; (g) BJ<sup>[63]</sup>; (h) MJ<sup>[64]</sup>

难<sup>[67]</sup>：一方面，为提升光固化技术中 HT-CMCs 浆料的固化速率，需增加光敏树脂含量，但这会降低最终 HT-CMCs 构件的致密度；另一方面，为提高 FDM 的层间结合强度，需引入柔性黏结剂，却会增加高温烧结后玻璃相析出风险，降低材料的耐高温性能。

### 2.2.2 工艺过程精度与缺陷控制

增材制造“逐层累加”的特性造成 HT-CMCs 构件的成形精度对工艺参数极为敏感<sup>[68]</sup>。激光功率、扫描速度、层厚等参数的微小波动都会对 HT-CMCs 构件的微观结构产生显著影响<sup>[69]</sup>。在 SLS 成形过程中，激光功率过高会导致 HT-CMCs 粉末过度熔化并产生飞溅，而功率不足则会出现烧结不充分，二者均会导致构件出现孔隙率超标或尺寸偏差；在 DLP 成形过程中，紫外光的强度分布不均会导致同一层固化深度差异，引发构件翘曲。此外，HT-CMCs 的脆性造成增材制造过程中产生的微裂纹难以自愈，且缺陷会随层间堆积不断累积<sup>[70]</sup>。在材料挤出技术中，喷嘴出口处剪切力变化会造成 HT-CMCs 浆料出现“挤出胀大”现象，

使层间界面形成缝隙，这些缝隙在后续烧结时会演变为贯通性裂纹。粉末床熔融成形过程中，由于 HT-CMCs 粉末导热系数低，激光照射区域的瞬时高温与周围环境的巨大温差而产生的热应力易导致构件出现分层缺陷，且这种缺陷难以通过在线监测实时捕捉。

### 2.2.3 后处理工艺调控

部分 HT-CMCs 增材制造技术 (VPP、ME 等) 的“生坯”需经脱脂、烧结等后处理才能获得最终性能，但后处理过程中的物理化学变化会放大前期工艺的缺陷<sup>[71]</sup>。在 FDM 生坯中的热塑性黏结剂需在一定温度范围内缓慢分解，若升温速率过快，会因气体逸出速率超过扩散速率而产生气泡；而烧结阶段的体积收缩若与脱脂后的孔隙分布不均叠加则会导致构件出现尺寸偏差；复杂结构内部通道的脱脂残留会带来烧结开裂隐患。此外，后处理过程中的温度场分布不均还会导致构件不同区域致密度的差异<sup>[72]</sup>。大型 HT-CMCs 构件烧结过程中边缘与中心存在温差，导致边缘致密度显著高于中

心,力学性能差异明显。这种不均一性在功能 HT-CMCs(如压电、导热 HT-CMCs)中会引发性能波动,严重限制其在精密器件中的应用。

#### 2.2.4 设备与成本制约

HT-CMCs 增材制造的产业化推进还受设备性能与经济性的限制<sup>[73-74]</sup>。粉末床设备的激光系统难以实现高熔点 HT-CMCs 的完全熔融;材料挤出设备的喷嘴易因 HT-CMCs 颗粒而磨损,导致尺寸精度下降。专用设备的研发滞后使 HT-CMCs 增材制造的工艺窗口狭窄,高熔点 HT-CMCs 的专用激光烧结设备尚未普及,导致其成形效率较低。此外,因高纯度 HT-CMCs 粉末、专用黏结剂及增材制造的长周期工艺,目前 HT-CMCs 增材制造的单位成本高于传统成形工艺。这种成本结构使其仅

适用于航空航天等高端领域小批量生产,而民用领域规模化应用仍面临障碍。

### 3 HT-CMCs 的增材制造工艺优化

在耐高温陶瓷基复合材料(HT-CMCs)的增材制造领域,材料固有属性与成形工艺的矛盾构成主要技术挑战。陶瓷材料高熔点与低韧性的特性导致打印过程极易出现裂纹、孔隙等缺陷<sup>[75-76]</sup>。多材料复合时,成分梯度控制精度不足会影响构件服役性能,而残余应力累积则严重影响结构可靠性。为突破这些技术瓶颈,亟须从材料特性设计、多材料打印及缺陷控制等维度开展针对性工艺优化(图4)。

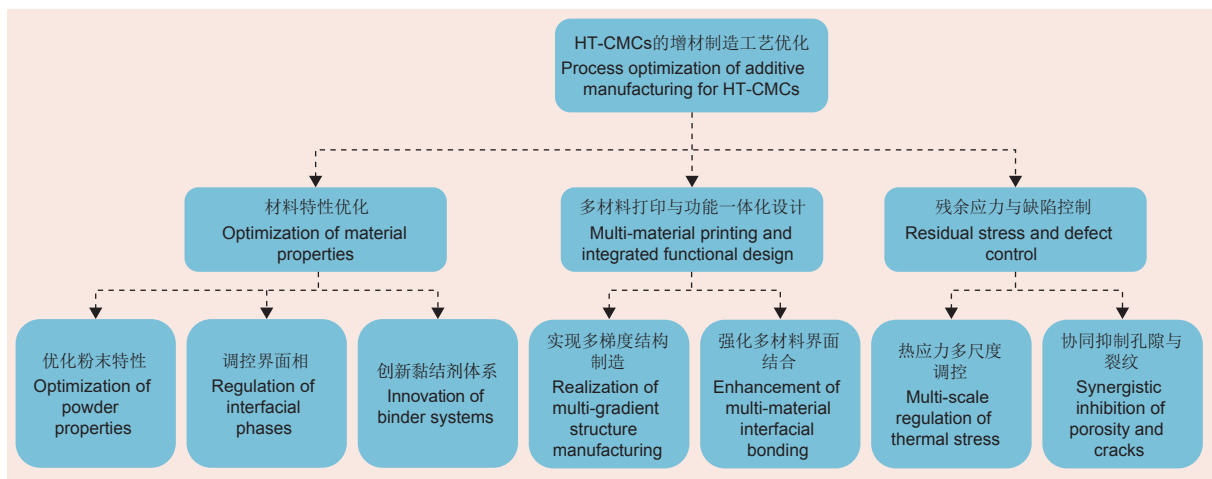


图4 HT-CMCs的增材制造工艺优化路线

Fig. 4 Optimization route for additive manufacturing process of HT-CMCs

### 3.1 材料特性优化

#### 3.1.1 优化粉末特性

在粉末床熔融技术中,粉末的流动性、粒径分布与形貌均影响铺粉均匀性和熔融致密性。粉末床熔融技术的主要优化手段包括:粒径控制、表面改性及核壳结构设计等。粒径控制:粉末特性对成形质量起着决定性的作用,粒径分布窄的球形粉末可提升松装密度,能使熔池内气体更顺畅地逸出,可有效减少气孔缺陷,提高成形件的致密度和力学性能<sup>[77]</sup>。表面改性:采用等离子球化等处理办法可有效降低粉末的表面粗糙度。光滑表面可减少颗粒间的范德华力从而抑制颗粒团聚现象,避免因局部过热或过冷而导致的成形缺陷,可提升铺粉均匀性与成形质量<sup>[78]</sup>。核壳结构设计:利用纳米包覆核壳结构设计,可降低烧结温度从而抑制晶粒异常长大<sup>[79]</sup>。

#### 3.1.2 调控界面

在连续纤维增强 HT-CMCs 中,界面的性能直接影响复合材料的整体性能,可通过三种方式调控界面。(1)通过化学气相沉积(CVD)在纤维表面沉积 PyC/BN 多层界面,可精准调控界面剪切强度,实现“裂纹偏转-纤维拔出”协同增韧机制。裂纹扩展时会因界面相的作用发生偏转而改变扩展方向,合适的界面结合力使纤维在受力时能逐渐拔出,从而提高材料的断裂韧性<sup>[80]</sup>。(2)通过等离子刻蚀或化学腐蚀处理纤维表面,形成纳米级沟槽结构,可增强界面机械互锁效应。当基体受力变形时,纤维表面的沟槽能与基体更好地咬合,提高界面传递载荷的能力,增强复合材料的整体性能<sup>[81]</sup>。(3)原子层沉积(ALD)技术能在原子尺度对界面进行改性。利用 ALD 在纤维表面构筑梯度过渡层可有效降低界面热阻,抑制纤维与基体间的元素扩

散。在高温服役环境下,过渡层能保持界面的稳定性,防止因元素扩散导致界面性能劣化,维持复合材料的力学性能<sup>[82]</sup>。

### 3.1.3 创新黏结剂体系

黏结剂在增材制造中对坯体成形质量及后处理至关重要<sup>[83]</sup>,其优化策略包括:开发新型复合黏结剂并采用分段热解工艺,低温预分解去除低沸点组分以减少挥发物对坯体结构的影响,中温碳化阶段精确控制残留碳量,避免残留碳与陶瓷基体反应<sup>[84]</sup>。引入纳米纤维素或海藻酸钠等功能性水基黏结剂,利用分子间氢键提升坯体强度,保证成形阶段形状稳定性且热解后无有害残留<sup>[85]</sup>。在光固化成形过程中调整光敏树脂配方(如添加纳米陶瓷颗粒),改善高固含量(>50%,质量分数)陶瓷浆料的流变性能,使其均匀填充模具型腔,经光固化后形成致密坯体,提高成形精度与产品质量<sup>[86]</sup>。

## 3.2 多材料打印与功能一体化设计

### 3.2.1 实现多梯度结构制造

多材料同步输送系统是实现梯度结构制造的硬件基础,能在高温环境应用尤为关键<sup>[87]</sup>。采用双螺杆挤出-多喷头协同打印装置,可实时调节送粉器速率与扫描路径<sup>[87]</sup>。DLP技术在梯度结构成形过程中,通过分层曝光能量调控,可实现孔隙率梯度或成分梯度的原位构建,从而满足隔热或高温力学性能的不同需求<sup>[88]</sup>。在工业高温炉的隔热内衬制造中,采用DLP技术制造的梯度结构内衬,能有效提升隔热效果,降低炉体热量散失。

### 3.2.2 强化多材料界面结合

在陶瓷-金属界面区域,利用激光原位合金化技术,通过精准调节激光能量密度,可诱导形成特殊过渡合金层,显著提升界面结合强度,保障在高温环境下多材料结构的整体性<sup>[89]</sup>。在航空发动机的热端部件中,陶瓷与金属的连接部位采用激光原位合金化技术可大幅提高部件在高温高压燃气环境下的可靠性<sup>[90]</sup>。在材料挤出成形过程中施加20~40 kHz超声振动,能有效促进陶瓷-金属界面的元素扩散<sup>[91]</sup>。超声振动产生的高频机械波,使界面处原子活性增强,扩散速率加快,可降低界面热阻,提高界面结合的牢固程度,有利于提高材料在高温下的性能<sup>[92]</sup>。此外,还可利用界面层厚度、成分、工艺参数等大量特征数据构建基于机器学习的界面优化模型,通过模型训练输出界面结合强度预测值<sup>[93-94]</sup>。根据预测结果反演最优界面设计方案,指导实际打印工艺,实现多材料界面结合性能的精准优化以适应高温复杂工况。在新型高温材料的研发和制造中,这种基于机器学习的界面优

化模型可大大提升研发效率和产品性能。

## 3.3 残余应力与缺陷控制

控制粉末床温度场是降低热应力的重要环节,对于高温增材制造至关重要。可采用电阻加热或红外辐射方式预热粉末床并在打印过程中维持层间温度稳定<sup>[95]</sup>。稳定的温度场可减小打印过程中的温度梯度,降低因温度变化过快产生的热应力。激光冲击强化(LSP)后处理是调控表面热应力的有效手段<sup>[96]</sup>。使用脉冲激光扫描材料表面使材料表层发生塑性变形,引入一定深度的压应力层抵消部分内部拉应力,有助于抑制裂纹的萌生与扩展,提高材料在高温下的疲劳寿命与可靠性。此外,优化扫描策略也能显著降低热应力<sup>[97-99]</sup>。采用多种扫描路径组合的策略可降低局部热积累。此外,可根据部件不同部位的散热情况,进行变功率扫描补偿散热差,进一步减少热应力产生,确保在高温环境下结构的稳定性。在制造大型高温反应釜时,这种优化扫描策略可有效减少制造过程中的热应力,提高反应釜的质量和可靠性。

能量密度调控是减少孔隙缺陷的关键,通过熔池红外监测技术可实时获取熔池温度、尺寸等信息进而实现动态调整激光功率与扫描速度<sup>[100-101]</sup>。热等静压(HIP)致密化处理是提升材料性能的重要后处理手段<sup>[102]</sup>,在高温高压条件下,材料内部的微孔隙会被压实,通过塑性流动填充孔隙,使材料致密度提升至99.5%以上。同时,材料内部的微观缺陷得到修复,晶界结合更紧密,可显著提高材料在室温及高温下的力学性能。此外,采用复合增韧技术可有效抑制裂纹扩展<sup>[103]</sup>。高温飞行器的机翼前缘等关键部件,采用复合增韧技术可有效提升其在高温高速气流冲击下的抗裂纹能力,保障飞行安全。

依赖黏结剂成形的增材制造工艺(如VPP、ME等)后续的脱脂与烧结是消除残余应力、减少缺陷的关键后处理环节<sup>[71]</sup>。脱脂过程需精确控制升温速率、保温时间与气氛(如空气、惰性气体),避免黏结剂快速热解产生的气体因排出不畅而导致坯体开裂或鼓泡。可采用阶梯式升温制度,在黏结剂分解的关键温度区间(200~600℃)缓慢升温并保温,可使气体有序挥发降低内应力。烧结阶段则需通过优化烧结温度、保温时间与降温速率,减少因晶粒异常生长或不均匀收缩产生的残余应力。

## 4 增材制造技术在 HT-CMCs 中的应用

### 4.1 航空航天领域

航空航天领域对材料的耐高温、轻量化、高强

度等性能有极高要求,增材制造技术的出现革新了耐高温陶瓷基复合材料(HT-CMCs)的加工模式<sup>[104]</sup>。在发动机热端部件制造中,Wang等<sup>[105]</sup>利用ME技术制备了轻量化、可承载、耐高温、宽频吸波的SiC陶瓷蜂窝超结构,该结构在室温环境、4.85~39.49 GHz的超宽频段内具有小于-10 dB的隐身效果,即使超过1600 °C的服役环境下,有效吸波带宽仍超过35 GHz(图5)。在大型预制件制造方面,Wang等<sup>[106]</sup>提出基于ME技术制造大型短碳纤维增强碳化硅(C<sub>sf</sub>/SiC)陶瓷基复合材料预制件,研究其固体负载、喷嘴直径和层高对复合材料稳定性的影响,为大规模HT-CMCs预成形件的制造提供参考。在发动机关键部件的实际应用中,Watanabe等<sup>[107]</sup>通过CVI结合SLS工艺制备的SiC/SiC涡轮护罩在75 h发动机测试中性能稳定,抗弯强度保持率超95%,这充分证明增材制造技术制备的HT-CMCs部件在航空发动机极端工况下的可靠性,为其在航空发动机上的进一步应用奠定基础。

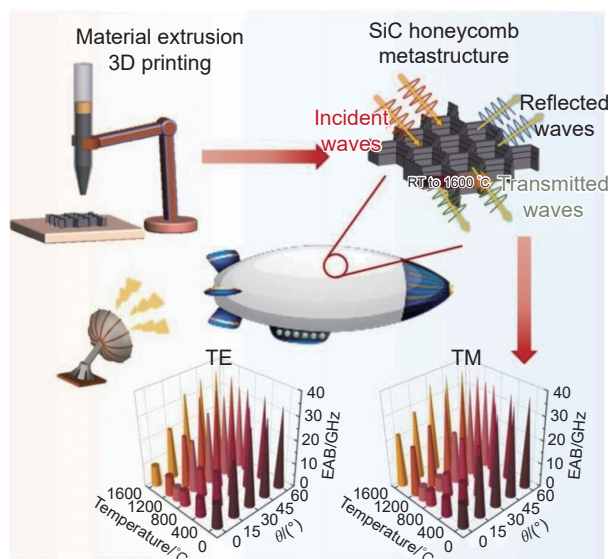


图5 ME技术制备SiC陶瓷蜂窝超结构及有效吸波带宽随温度的变化<sup>[105]</sup>

Fig. 5 SiC ceramic honeycomb superstructure fabricated by ME technology and the variation of effective absorbing bandwidth with temperature<sup>[105]</sup>

#### 4.2 能源动力领域

能源动力设备需在高温、高压、强腐蚀等极端工况下服役,增材制造为HT-CMCs应用开拓新方向<sup>[108]</sup>。黏结剂喷射(BJ)技术通过逐层喷射黏结剂固化陶瓷粉末可制造功能梯度结构的高温反应器内衬。煤化工气化炉内衬利用BJ技术制造,可实现内层采用高铬含量陶瓷基复合材料用于抵御高温,外层选用低热导率材料延长反应器耐腐蚀寿

命。SLA和DLP技术凭借高精度成形优势可用于固体氧化物燃料电池(SOFC)部件制造<sup>[109]</sup>。

#### 4.3 其他高端制造领域

选区激光烧结(SLS)技术制备的发动机气门,采用SiC颗粒增强Al<sub>2</sub>O<sub>3</sub>基复合材料,凭借高硬度与低膨胀特性,在800 °C高温下仍能维持高精度配合间隙,减少发动机漏气,提升燃油经济性。Hu等<sup>[110]</sup>利用数字光处理(DLP)3D打印技术制备铝掺杂SiAlOC陶瓷传感器。通过蜂窝状多孔结构设计(孔隙率50%),材料在1000 °C下介电常数稳定在9.5±0.2,压力灵敏度达0.02 mV/kPa,温度分辨率为0.1 °C。特殊的梯度孔隙结构(表面100 μm→内部500 μm)实现了应力-温度信号的解耦响应,已应用于航空发动机燃烧监测与工业高温炉实时控制。Zhang等<sup>[111]</sup>通过光固化3D打印技术制备Al<sub>2</sub>O<sub>3</sub>-ZrO<sub>2</sub>仿生层状复合材料,模仿天然贝壳珍珠层结构定向排列Al<sub>2</sub>O<sub>3</sub>片晶(厚度1 μm)与ZrO<sub>2</sub>纳米颗粒,形成多级增韧机制,复合材料的断裂韧性达16.9 MPa·m<sup>1/2</sup>,比传统陶瓷提升4倍,同时在1200 °C下抗弯强度保持率>70%。

增材制造技术通过精确控制材料的微观结构与宏观形状,可有效解决极端工况下材料的耐高温、抗腐蚀及复杂载荷等难题,持续拓展HT-CMCs在航空航天发动机高温部件、能源工业高压反应器等极端环境中的应用边界,为高性能材料制造与尖端装备发展注入新动能。

## 5 结束语

耐高温陶瓷基复合材料(HT-CMCs)的增材制造技术正推动航空航天、能源动力等高端装备快速发展。数字化成形工艺已实现复杂结构的精准制造,通过材料特性优化、多材料打印与功能一体化设计、残余应力与缺陷控制等手段可显著提升材料综合性能。然而,当前技术仍面临多材料打印界面结合强度不足、工艺参数智能调控能力弱、设备模块兼容性差及材料回收利用率低等核心挑战,制约其工程化应用进程。

未来HT-CMCs增材制造技术将沿多维度创新路径突破,未来发展应重点关注以下三方面:

(1)材料与工艺的协同创新:未来陶瓷增材制造将涉及多材料打印,以实现零件的多功能一体化和梯度功能结构。应进一步完善多材料打印技术,提高不同材料之间的结合强度和界面质量;并开发能够兼容多种陶瓷材料复合打印的工艺和技术,满

足复杂功能部件的制造需求。

(2)智能化制造体系构建:建立覆盖“数字控制-实时监控-参数优化”系统,利用AI算法动态调控打印技术工艺参数,通过缺陷预警模型与数字仿真降低试错成本,实现从设计到打印的全流程智能管控。

(3)模块化技术升级与循环制造:基于模块化设计理念开发可快速切换的打印头、供料系统等标准化模块,实现多技术的灵活组合;同时,创新陶瓷废料回收技术,通过粉末再生、浆料循环利用等手段,提升材料利用率,推动陶瓷增材制造从定制化生产向规模化工业制造转型。

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收稿日期: 2025-07-01; 录用日期: 2025-08-22

基金项目: 国家重点研发计划项目(2024YFB3714502); 国家自然科学基金(52130204); 陕西省重点研发计划项目(2024GX-YBXM-220, 2024CY-GJHX-29, 2024GX-ZDCYL-03-03); 宁波市重大专项(2025Z070)

通讯作者: 苏海军(1981—), 男, 博士, 教授, 研究方向为陶瓷基复合材料的制备与性能调控, 联系地址: 陕西省西安市碑林区友谊西路 127 号西北工业大学(710072), E-mail: suhaijun@nwpu.edu.cn

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