

燃气轮机不锈钢机匣 3D 打印复合型芯整体精密铸造技术研究

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摘要: 本研究针对燃气轮机马氏体沉淀硬化不锈钢机匣, 重点攻克了传统锻焊工艺导致的尺寸精度低与生产成本高等工程瓶颈。研究采用 VX2000 型 3DP 设备制备大尺寸复合型芯, 原料选用 70~140 目进口石英砂, 并针对内环、外环及支板部位设置了轴向 18.0‰等三维差异化缩尺比例, 以实现精密尺寸补偿。通过在型芯内部设计空间网格化结构与Φ30mm 随形主排气通道, 结合高耐火度锆英粉特种涂料浸涂工艺, 有效解决了复杂薄壁部位(最薄处 5mm)的排气与充型难题。此外, 利用 AOD 炉外精炼技术对 C、Mn、Cr 等化学元素进行窄区间内控, 显著提升了钢水纯净度。实际验证表明, 该成套技术成功消除了缩孔、缩松等缺陷, 使机匣的尺寸精度达到焊接机匣国家标准, 为我国高端能源装备提供了关键的自主制造技术保障。

关键词: 3D 打印复合型芯; 不锈钢机匣; 精密铸造; 尺寸精度

Research on Integral Precision Casting Technology for Stainless Steel Gas Turbine Casings Based on 3D-printed Composite Cores

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Abstract: This study focuses on martensitic precipitation-hardening stainless steel casings for gas turbines, specifically overcoming engineering bottlenecks such as low dimensional accuracy and high production costs associated with traditional forging and welding processes. Large-scale composite cores were prepared using a VX2000 3DP system with 70–140 mesh imported quartz sand. To achieve precise dimensional compensation, three-dimensional differential shrinkage ratios, such as an axial ratio of 18.0‰, were implemented for the inner ring, outer ring, and struts. By designing spatial-gridded structures within the cores along with Φ30mm conformal main venting channels, and combining this with a specialized high-refractoriness zircon-based coating immersion process, the challenges of gas evolution and filling in complex thin-walled sections (as thin as 5mm) were effectively resolved.

Keywords: 3D Printed Composite Core; Stainless Steel Casing; Precision Casting; Dimensional Accuracy

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1 前言

燃气轮机大尺寸不锈钢机匣结构复杂，内外环及流道面为非加工面，存在大面积薄壁区域（最薄处仅 5mm），热节分布弥散，传统分项锻造与焊接拼装工艺导致成分不均匀、尺寸精度低、生产周期长、制造成本高等问题，难以满足高性能燃气轮机对机匣一致性与可靠性的严苛要求。

本研究针对燃气轮机马氏体沉淀硬化不锈钢机匣，开展了以 3D 打印复合型芯为核心的整体精密铸造技术研究，重点解决复杂薄壁充型、精密尺寸控制及内部质量控制等关键工程问题。

2 试验过程

(1) 工艺方案设计：采用 3D 打印复合型芯与重力铸造相结合的整体精密铸造方案。型芯采用 VX2000 型 3DP 喷墨打印设备制备（最大成形尺寸 2000mm×1000mm×1000mm），原料为进口 SiO₂ 石英砂（70~140 目），粘结剂为改性呋喃树脂（1.5%~2.0%），固化剂为甲苯磺酸（占粘结剂 25%~35%），成形精度 0.2mm。针对机匣不同部位（内环、外环、支板）分别设置三维差异化缩尺比例（轴向 18.0%，外环 16.5%~17.5%，支板 17.0%），并设计明/暗冒口与冷铁组合补缩系统及底注式挡渣浇注系统。

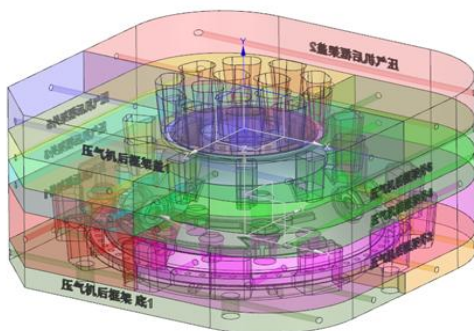


图 1 机匣整体精密铸造工艺示意图和 3D 砂型组型示意图

Figure 1 Schematic diagram of the integral precision casting process for the casing

(2) 空间网格化 3D 打印型芯制备：采用 $\Phi 3\text{mm}$ 球体结构网格单元（1mm 网格间隙）对砂型内部进行网格化设计，在每个支板间隔中心部位设置单条 $\Phi 30\text{mm}$ 随形主排气通道；使用

红外烘干工艺促进粘结剂固化以获得理想型芯强度；结合 3D 打印砂模烧散精铸型壳制备技术，将 3D 打印砂型与熔模铸造理念结合，进一步提升铸件表面光洁度。

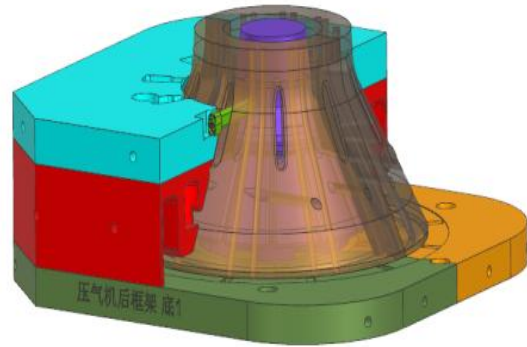


图 2 燃气轮机不锈钢机匣 3D 打印型芯空间网格化结构示意图

Figure 2 Schematic diagram of the spatial-gridded structure of 3D-printed cores for stainless steel gas turbine casings

(3) 特种涂料开发与冶炼纯净化控制：开发以高耐火度锆英粉为主骨料的水基特种涂料，添加刚玉粉、改性硅酸镁铝及润湿渗透剂等，采用浸涂工艺均匀施涂后入炉烘烤；利用 AOD 炉外精炼有效去除 S、P 等有害元素，并对各化学元素（C、Mn、Cr、Ni、Cu 等）含量进行严格窄区间内控。



图 3 特种涂料浸涂效果图

Figure 3 Resulting image of special coating dip coating

3 试验结果及分析

实际浇注验证结果表明，空间网格化 3D 打印型芯设计有效解决了 3D 打印砂型发气量大、透气性差及无法选区性能调控的问题，实现了复杂薄壁支板部位（最薄 5mm）的完整充型；三维差异化缩尺比例设计与优化补缩通道设计成功消除了缩孔、缩松等铸造缺陷；AOD 精炼与成分窄区间控制显著提升了钢水纯净

度与材料整体性能一致性；特种涂料浸涂工艺使铸件表面质量达到高标准，机匣尺寸精度达到焊接机匣国家标准。

4 结论

本研究首次采用 3D 打印复合砂型精密铸造方法，结合 3D 打印砂模烧散精铸型壳制备技术，突破了复杂薄壁不锈钢机匣整体精密铸造的多项关键技术瓶颈。所形成的成套技术（整体铸造工艺设计、高精度 3D 打印型芯制备、充型与质量控制）实现了燃气轮机不锈钢机匣的整体精密成形，产品整体成分性能一致性好、尺寸精度高、内部质量优良，有效解决了传统制造过程中成分不均匀、生产周期长、成本高等问题。项目成果已成功应用于多型燃气轮机不锈钢机匣产品，为我国舰船、航空、能源等领域提供了关键铸件保障，具有显著的经济效益与社会价值，并对推动我国绿色精密铸造技术发展具有重要示范意义。

参考文献：

- [1] Chhabra, J., Singh, R., Pandey, P.M. et al. Investigations on dimensional accuracy and surface roughness of stainless steel castings using 3D printed sand molds. *Rapid Prototyp J* 24, 1500–1512 (2018).
- [2] Guan, S., Wang, L., Wu, J. et al. Microstructure and mechanical properties of martensitic precipitation hardening stainless steel for gas turbine components. *Mater Des* 132, 210–221 (2017).
- [3] Shishkovsky, I. *New Trends in 3D Printing*. IntechOpen, London (2016).
- [4] Liu, Z., Wang, X., Jiang, Z. Cleanliness control of martensitic stainless steel during AOD and LF refining processes. *Ironmak Steelmak* 45, 632–641 (2018).
- [5] Yan, X., Li, C., Zhang, H. Precision casting of large-scale gas turbine casings: A review of current technologies. *Foundry Trade J* 192, 55–62 (2018).
- [6] Sing, S.L., Yeong, W.Y. Binder jetting of metals and ceramics: Process and applications. *Powder Technol* 365, 45–57 (2020).
- [7] Lu, L., Wang, J., Sun, B. Effect of cooling rate on the precipitation and properties of 17-4PH stainless steel castings. *Metall Mater Trans A* 49, 321–333 (2018).
- [8] He, Y., Zhao, J. Development of zircon-based water-borne coatings for precision sand casting of high-alloy steels. *Surf Coat Technol* 350, 112–120 (2018).
- [9] Jiang, J., Chen, X., Lu, Z. Design and optimization of venting systems in 3D printed complex sand cores. *J Manuf Sci Eng* 141, 091005 (2019).
- [10] Campbell, J. *Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design*. Butterworth-Heinemann (2015).
- [11] Jolly, M. *Professor John Campbell's 10 Rules for Making Good Castings*. Cast Metals Federation (2008).
- [12] Zhao, J., Kang, J. Shrinkage compensation and dimensional control in large-scale steel casting using 3D printing. *J Mater Res Technol* 9, 8812–8824 (2020).
- [13] Wang, G., Zhang, Y. Precision forming of aero-engine turbine casings: Integration of 3DP and investment casting. *Aerosp Sci Technol* 85, 120–132 (2019).
- [14] Hou, D., Wang, D.Y., Jiang, Z.H. et al. Investigation on Slag–Metal-Inclusion Multiphase Reactions During Electroslag Remelting of Die Steel. *Metall Mater Trans B* 52, 478–493 (2021).