

博士学位论文

激光粉末床熔融 IN718/CuCrZr 异质材料
工艺与性能研究

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**Printing Process and Performance of IN718/CuCrZr
Heterogeneous Materials Fabricated by Laser Powder Bed
Fusion**

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#####大学博士学位论文

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摘 要

铜合金/镍基高温合金异质材料可将铜合金的高导热特性，以及镍基高温合金的耐高温、高机械强度和耐腐蚀性等性能集成于单一零件中，在航空航天、集成电路等领域的火箭发动机燃烧室、燃油喷嘴、散热器和换热器等复杂构件中展现出巨大应用潜力。激光粉末床熔融（Laser powder bed fusion, LPBF）作为金属增材制造应用最广泛的技术之一，能够精确控制材料在零件内部的分布，为精细跨尺度、复杂结构异质材料构件的高性能、多功能性主动设计与制造提供了创新途径。其中，三维异质材料 LPBF 技术允许零件内部的材料沿 XYZ 三维方向进行定制性变化，增加了材料在三维空间分布的自由度。然而，目前三维异质材料 LPBF 技术仍存在设备定制成本高、专用设计的粉末分配系统与单一材料 LPBF 设备适配程度低等问题。其次，水平以及倾斜/曲线结合界面仍存在 LPBF 成形机理不明晰、界面微观组织与力学性能调控难等挑战。此外，目前通过复杂材料布局与结构设计提升结构性能/功能的潜力仍未被深入探索。针对上述问题，本课题基于 IN718 镍基高温合金和 CuCrZr 铜合金，从异质材料 LPBF 成形方法、成形机理、互锁界面强化方法、异质材料创新结构与制造等方面开展系统研究，旨在为异质材料 LPBF 成形提供理论基础与科学依据。主要研究内容如下：

（1）针对设备定制成本高、专用设计的粉末分配系统与单一材料 LPBF 设备适配程度低等问题，开展基于柔性刮板扫粉和全幅面吸粉的异质材料 LPBF 成形方法研究。分别基于柔性刮板扫粉和全幅面吸粉原理，设计并开发了兼容于单一材料 LPBF 设备的异质材料成形模块，实现了三维异质材料结构的 LPBF 成形，验证了上述两种成形方法的可行性。揭示了不同成形方法的粉末去除机理，并阐明了粉末去除工艺优化过程的影响因素，讨论了异质材料 LPBF 过程的粉末消耗、材料污染等关键问题。材料预置精度研究结果表明，单一材料特征的尺寸应尽量大于 0.5 mm，其材料位置误差小于 $\pm 50\ \mu\text{m}$ 。相比基于柔性刮板扫粉的方法，基于全幅面吸粉原理的异质材料 LPBF 成形方法在提高成形效率、材料预置精度控制、减少成形过程粉末消耗量等方面更具优势。

（2）针对不同界面结合方式（垂直、水平、倾斜和曲线界面结合）的成形机理不明晰、界面微观组织与性能调控等难题，开展 IN718/CuCrZr 异质材料的 LPBF 成形机理与组织性能研究。结果表明，对于垂直结合界面，其界面熔池的熔化行为是逐层动态变化的，且不同材料的成形顺序会改变界面的微观组织与结合性能。对于水平结合界面，在界面处采用高激光能量输入、平行于界面的扫描策略以及界面模型重叠有利于促进界

面的元素混合并增加元素扩散区宽度，提高界面结合强度。相比非重叠样品，界面重叠样品的极限抗拉强度提升超过 30%。对于倾斜/曲线结合界面，不同界面结合角度、材料成形顺序会显著改变界面处的材料混合与扩散行为。

(3) 针对异质材料的界面结合可靠性提升难题，开展基于分形互锁设计的异质材料界面强化方法研究。设计并制备了三种具有不同分形互锁界面的 IN718/CuCrZr 异质材料 (N0、N1 和 N2)。研究了分形互锁界面设计对界面特性、热力学行为和力学性能的影响，进一步讨论了界面变形行为与强化机制。结果表明，主动设计的分形互锁界面可以改善界面应力分布，改变断裂路径，增加能量耗散。界面拉伸-剪切、张力拉伸以及弯曲试验结果表明，分形互锁界面设计可提高界面结合强度。N0、N1 和 N2 样品的极限弯曲强度分别为 502 ± 15 MPa、 577 ± 11 MPa 和 515 ± 20 MPa，其中 N1 样品比 N0 样品的极限弯曲强度提升约 15%。

(4) 通过材料布局与结构设计结合，实现了 IN718/CuCrZr 异质材料仿生蜂窝结构与散热/换热结构的创新设计及 LPBF 制造。设计并 LPBF 制造了五种异质材料仿生蜂窝结构 (HA、Ni-B、Ni-C、Cu-B 和 Cu-C)，进一步研究了其宏观形貌、成形尺寸精度、界面微观组织以及力学性能。结果表明，材料布局设计会改变异质材料仿生蜂窝结构受力过程中的变形与断裂行为。HA 结构的材料布局设计不仅提高了纵向拉伸受力过程的延展性和纵向压缩受力过程失效稳定性，还提升了结构在法向方向压缩过程的稳定性。此外，材料的布局设计改变了 B 型 (Ni-B 和 Cu-B) 和 C 型 (Ni-C 和 Cu-C) 异质材料结构内部不同材料区域的应力分布和断裂行为。进一步设计并制造了异质材料散热结构和换热结构。结构特征分析表明，异质材料散热结构和换热结构具有良好的成形质量，展现了其在电子芯片、集成电路等高功率热流密度场景的应用潜力。

关键词：激光粉末床熔融；异质材料；成形机理；微观组织；力学性能

Abstract

Copper alloy/nickel-based superalloy heterogeneous materials can integrate the high thermal conductivity of copper alloys and the high-temperature resistance, high mechanical strength and corrosion resistance of nickel-based superalloys into a single part. They have shown great application potential in complex components such as rocket engine combustion chambers, fuel nozzles, heat sinks, and heat exchangers in fields such as aerospace and integrated circuits. Laser powder bed fusion (LPBF), as one of the most widely applied techniques in metal additive manufacturing, can precisely control the spatial distribution of different materials within heterogeneous material parts, which provides an innovative approach for the high-performance and multi-functional active design and manufacturing of fine cross-scale and complex-structured heterogeneous material components. In particular, three-dimensional (3D) heterogeneous material LPBF technology enables spatially material variations along XYZ directions in the parts, increasing the degree of freedom of material distribution in 3D space. However, at present, 3D heterogeneous material LPBF technology still faces problems such as high equipment customization cost, low compatibility between the specially designed powder distribution system and the single-material LPBF equipment. Secondly, there are still challenges such as the unclear printing mechanism and the difficulty in regulating the microstructure and mechanical properties of the horizontal and inclined/curved bonding interfaces. In addition, the potential to enhance structural performance/function through complex material layout and structural design has not yet been deeply explored. To address the above issues, based on the IN718 nickel-based superalloy and CuCrZr copper alloy, this research focused on the heterogeneous material LPBF method, printing mechanisms, interlocking interface strengthening methods, and innovative structural design and manufacturing of heterogeneous materials. The purpose is to provide theoretical foundations and scientific reference for LPBF of high-quality metal heterogeneous components. The main contents include:

(1) Aiming at the issues of high equipment customization cost, low compatibility between the specially designed powder distribution system and the single-material LPBF equipment, LPBF printing method of heterogeneous materials based on flexible scraper powder sweeping and full-width powder suction were investigated. Based on the principles of flexible scraper powder sweeping and full-width powder suction, the heterogeneous material LPBF printing module compatibles with single-material LPBF equipment were designed and developed, achieving the LPBF printing of three-dimensional heterogeneous material structures and

verifying the feasibility of the above printing methods. The powder removal mechanism in different printing methods was revealed, and the influencing factors of the powder removal process optimization process were clarified. The critical issues such as powder consumption and material contamination existing in the LPBF process of heterogeneous materials were discussed. The results on the preset accuracy of materials show that the size of a single material feature should be as large as 0.5 mm as possible, and the material position error can be less than $\pm 50\text{ }\mu\text{m}$. Compared with the method based on flexible scraper powder sweeping, the method based on full-width powder suction exhibited the advantages in improving printing efficiency, controlling the pre-setting accuracy of materials, and reducing powder consumption.

(2) Aiming at the problems such as the unclear printing mechanism of different interfaces (vertical, horizontal, inclined and curved interfaces), and the regulation of interfacial microstructure and mechanical properties, the microstructure and bonding performance of IN718/CuCrZr heterogeneous materials printed by LPBF were systematically investigated, and the printing mechanism of LPBF-processed heterogeneous materials was revealed. The results show that the melting behavior of the melt pool at the vertical bonding interface can change dynamically layer by layer during LPBF process, and different printing sequences can change the interfacial microstructure and interface bonding strength. For the horizontal bonding interface, adopting the high laser energy input, laser scanning strategies parallel to the interface, and model overlapping at the interface were conducive to promoting the element mixing and increasing the width of the diffusion zone, thus enhancing the interface bonding strength. Compared with non-overlapping samples, the ultimate tensile strength of overlapping samples increased by more than 30%. For the inclined/curved bonding interface, different interface bonding angles and material printing sequences can significantly change the material mixing and diffusion behaviors at the interface.

(3) To address the challenge of improving the reliability of interface bonding of LPBF-processed heterogeneous materials, the interface strengthening method of heterogeneous materials based on hierarchical interlocking design were investigated. Three types of IN718/CuCrZr heterogeneous material structures with interlocking interfaces (N0, N1 and N2) were designed and fabricated by LPBF. The influence of hierarchical interlocking interface design on interface characteristics, thermodynamic behavior and mechanical properties was investigated, and the interface printing mechanism and interface strengthening mechanism were further discussed. The actively hierarchical interlocking interface design can improve the stress distribution of the interface, change the fracture path and increase energy dissipation. The results of interface tensile-shear, tension tensile and flexural tests show that the hierarchical

interlocking interface design can improve the interface bonding strength. The ultimate flexural strength of N0, N1 and N2 samples was 502 ± 15 MPa, 577 ± 11 MPa and 515 ± 20 MPa, respectively. The ultimate flexural strength of N1 samples increased by approximately 15% compared with N0 samples.

(4) By integrating material layout with structural design, innovative heterogeneous material bionic honeycomb structures and heat-dissipating/exchanging structures were designed and manufactured by LPBF. Five types of heterogeneous material bionic honeycomb structures (HA, Ni-B, Ni-C, Cu-B and Cu-C) were designed and manufactured, and their macroscopic morphology, printing dimensional accuracy, interfacial microstructure and mechanical properties were further investigated. The results show that the material layout design can change the deformation and fracture behavior of the bionic honeycomb structures. The material layout design of the HA structure can not only improve the ductility during the longitudinal tensile process and the failure stability during the longitudinal compressive process, but also enhance the failure stability of the structure during the compression process in the normal direction. In addition, the material layout design changed the stress distribution and fracture behavior of type B (Ni-B and Cu-B) and type C (Ni-C and Cu-C) heterogeneous material structures. The heterogeneous material heat dissipation and heat exchange structures were further designed and fabricated by LPBF. The analysis of structural characteristics indicated that the heterogeneous material heat dissipation and heat exchange structures exhibited good printing quality, demonstrating their application potential in high-power heat flux density scenarios such as electronic chips and integrated circuits.

Keywords: Laser powder bed fusion; Heterogeneous materials; Printing mechanism; Microstructure; Mechanical performance