

中图分类号: XXXXX

单位代码: XXX

学 号: XXXXX

博士学位论文

Doctoral Dissertation of XXXXX

水锤式金属熔滴按需喷射增材制造技术及机理研究
Research on Technology and Mechanism of Water
Hammer-Based On-Demand Metal Droplet Jetting for
Additive Manufacturing

学科专业: 机械工程

研究方向: 机械制造及其自动化

作者姓名: XXX

指导教师: XXX 教授

二〇二五年十一月

**Research on Technology and Mechanism of Water
Hammer-Based On-Demand Metal Droplet Jetting for
Additive Manufacturing**

A Dissertation Submitted for the Degree of Doctor of Philosophy

Candidate: xxx

Supervisor: xxxxx

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摘 要

金属增材制造作为实现复杂结构一体化成形与个性化定制生产的关键技术，已在航空航天、医疗植入、汽车制造等高端领域展现出不可替代的应用价值，成为全球制造业转型升级的重要方向。以激光粉末床熔融为代表的传统高能束增材制造技术，虽具备高精度复杂成形能力，但依赖高功率激光与高成本金属粉末，存在能耗与成本高等问题；同时，其大热输入与急速熔凝过程极易诱发应力、变形及冶金缺陷，增加了成形机理解析与过程调控难度，制约了工程应用推广。相比之下，熔滴喷射式金属增材制造技术以金属丝材为原料，将其熔化成液态金属后按需喷射熔滴逐层沉积，具有热输入低且精准可控、原材料适用性广、成本和能耗低等优势。然而，国内外现有的气动式、压电式和电磁式熔滴喷射技术存在喷射频率低、稳定性不足及喷头结构复杂等问题，限制了其发展。此外，我国尚无原创的、在技术指标接近或超越国外的高效稳定按需熔滴喷射技术。

本文提出一种利用水锤效应的精密高效金属熔滴按需喷射新方法，并将其应用于金属增材制造领域。该技术通过压电驱动喷管在轴向进行微米级往复运动，使喷管内的熔融金属与喷管底部内壁形成显著的速度差，进而产生水锤脉冲压力，实现金属熔滴的按需喷射。本文围绕熔滴的喷射机理与沉积成形机理开展了系统研究，主要研究成果如下：

(1) 提出水锤式金属熔滴按需喷射增材制造新技术。不同于依赖外部加压或内置运动部件的传统熔滴喷射方式，该方法通过驱动喷管进行微米级轴向往复运动，利用管壁这一流体“边界”的主动往复运动产生瞬态水锤压力，实现了对喷孔处熔融金属的非接触式能量注入与精准按需喷射，可稳定获得直径 $60\sim 500\ \mu\text{m}$ 范围的熔滴，且喷射频率高于现有技术。根据喷管系统运动形式，将该技术分为基于阻尼自由振动和基于受迫振动的金属熔滴按需喷射两种模式，分别适用于高精度和高效率制造需求。

(2) 建立了微尺度边界驱动水锤效应理论模型，揭示了边界运动-压力波耦合机制，阐明了喷管微运动参数与脉冲压力波形的定量映射关系，以及压力波在微米级流道内的传播、反射与叠加规律；揭示了压力波-熔滴喷射协同机制，阐明了熔体喷出、液桥断裂、熔滴成形的微观动力学过程。定量分析了喷管振幅、液位高度、激励信号持续时间以及喷孔直径对于自由振动模式下脉冲压力演化及熔滴喷射行为的影响规律。研究表明，随着水锤脉冲压力的增大，熔滴喷射速度显著提高，且喷射体积同步增大。

(3) 率先利用机械系统受迫振动的高频特性来进一步提升水锤式熔滴喷射的频率上限, 实现了最高 5 kHz 的金属熔滴按需稳定喷射, 喷射频率远超国内外同类技术。研究表明, 机械系统的受迫振动可有效抑制机械系统残余振动, 不仅能实现更高的喷射频率, 还可显著增强高频喷射过程的稳定性。

(4) 系统开展了自由振动模式下金属熔滴点-线-面-体逐级成形实验, 揭示了多尺度成形中几何形貌与成形质量的演化规律, 阐明了工艺参数对结构构建稳定性的调控机制。定量分析了搭接率、喷头打印速度及基板温度对单滴沉积、单道成形、单层多道及多层三维成形质量的影响。结果表明, 优化搭接率与打印速度可提升道间连续性与表面质量, 提高基板温度有利于改善铺展与层间结合, 从而实现致密稳定的三维成形。

(5) 建立了受迫振动熔滴按需喷射单道及三维成形传热模型, 结合实验与数值模拟, 揭示了成形过程中热量传递与积累的演化规律, 阐明了工艺参数对热行为及成形质量的调控机制。定量分析了基板温度、打印速度及喷射频率对热输入与成形质量的影响。结果表明, 熔池热量与质量输入比是决定成形性能的关键因素; 提高基板温度与喷射频率有助于提升熔池温度并促进熔滴充分熔合, 从而改善成形件力学性能。

(6) 以铝硅合金为原材料, 开展了水锤式金属熔滴按需喷射及成形实验, 揭示了工艺参数对成形均匀性与层间结合质量的影响规律。定量分析了打印频率与打印速度对成形稳定性的调控作用。结果表明, 提高打印频率或降低打印速度可显著改善成形均匀性与层间冶金结合; 该方法可实现低密度、高熔点金属的稳定按需喷射, 成形件表现出良好的力学性能与工艺稳定性, 具备低成本高性能制造的应用潜力。

本文围绕着水锤式金属熔滴按需喷射增材制造技术, 系统开展了相关理论研究与工艺实验, 形成了较为完整的机理认知与方法体系, 为该技术的进一步发展及工程化应用奠定了坚实的理论与技术基础。

关键词: 水锤效应; 金属增材制造; 熔滴按需喷射; 熔滴沉积; 数值模拟

Abstract

Metal additive manufacturing , as a key enabling technology for the integrated fabrication of complex structures and personalized production, has demonstrated unique application value in high-end fields such as aerospace, medical implants, and automotive manufacturing, and has become a key driver of transformation in the global manufacturing industry. Traditional high-energy beam-based AM technologies, represented by laser powder bed fusion, offer high-precision fabrication of complex geometries; however, they rely on high-power lasers and costly metal powders, resulting in substantial energy consumption and high production costs. In addition, the large thermal input and rapid melting–solidification processes tend to induce residual stresses, deformation, and metallurgical defects, thereby complicating mechanistic understanding and process control, and ultimately limiting their broader engineering application. In contrast, droplet-based metal AM employs metal wire as feedstock, which is melted into liquid metal and deposited layer by layer via droplet-on-demand ejection. This approach features low and precisely controllable thermal input, broad material adaptability, and reduced cost and energy consumption. Nevertheless, existing pneumatic, piezoelectric, and electromagnetic droplet-on-demand techniques suffer from low ejection frequency, limited stability, and complex nozzle structures, which constrain their further development. Moreover, no independently developed high-efficiency and stable droplet-on-demand technology with technical performance comparable to or exceeding that of international counterparts has yet been established in China.

This study proposes a novel high-precision and high-efficiency droplet-on-demand metal ejection method based on the water hammer effect and applies it to metal additive manufacturing . In this approach, piezoelectric actuation drives the nozzle to undergo axial micron-scale reciprocating motion, generating a transient velocity discontinuity between the molten metal inside the nozzle and the inner wall near the nozzle base. This, in turn, induces a water-hammer-induced pressure pulse, enabling controlled droplet-on-demand ejection of molten metal. The present work systematically investigates both the droplet ejection mechanism and the deposition and forming mechanisms, with the main findings summarized as follows:

- (1) A novel water-hammer-driven droplet-on-demand metal AM technique is proposed.

Distinct from conventional droplet jetting methods that rely on external pressurization or internal moving components, the proposed approach utilizes the active reciprocating motion of the nozzle wall-serving as a dynamic fluid boundary-to generate transient water-hammer pressure. This enables non-contact energy input into the molten metal at the orifice and achieves precise droplet-on-demand ejection. The method can stably produce droplets with diameters ranging from 60 to 500 μm , with achievable ejection frequencies exceeding those of existing techniques. Based on the dynamic characteristics of the nozzle system, the technique is further classified into two modes: damping-induced free vibration and forced vibration-driven droplet-on-demand ejection, which are suitable for high-precision and high-efficiency manufacturing, respectively.

(2) A theoretical model of microscale boundary-driven water hammer was established, revealing the coupling mechanism between boundary motion and pressure waves. The quantitative mapping between nozzle micro-motion parameters and the resulting pressure pulse waveform was elucidated, along with the propagation, reflection, and superposition behavior of pressure waves within micron-scale channels. Furthermore, the coupled dynamics between pressure waves and droplet ejection were clarified, uncovering the microscale processes governing melt extrusion, liquid bridge breakup, and droplet formation. Quantitative analyses were conducted to evaluate the effects of nozzle vibration amplitude, liquid column height, excitation signal duration, and orifice diameter on the evolution of pressure pulses and droplet-on-demand ejection behavior under the free vibration mode. The results indicate that increasing the water-hammer-induced pressure pulse significantly enhances droplet ejection velocity, accompanied by a corresponding increase in droplet volume.

(3) The high-frequency characteristics of forced vibration in the mechanical system were, for the first time, exploited to further extend the frequency limit of water-hammer-driven droplet-on-demand ejection. Stable metal droplet-on-demand ejection was achieved at frequencies up to 5 kHz, significantly exceeding those of comparable domestic and international technologies. The results demonstrate that forced vibration effectively suppresses residual oscillations in the mechanical system, thereby enabling higher ejection frequencies while substantially improving the stability of high-frequency droplet ejection.

(4) A systematic investigation was conducted on the hierarchical formation process from

point to line, surface, and bulk structures under the free vibration droplet-on-demand mode. The evolution of geometric morphology and forming quality across multiple scales was revealed, and the regulatory mechanisms of process parameters on structural stability were elucidated. Quantitative analyses were performed to assess the effects of overlap ratio, nozzle printing speed, and substrate temperature on single-droplet deposition, single-track formation, multi-track single-layer deposition, and multi-layer three-dimensional fabrication. The results show that optimizing the overlap ratio and printing speed improves inter-track continuity and surface quality, while increasing substrate temperature promotes droplet spreading and interlayer bonding, thereby enabling dense and stable three-dimensional structures.

(5) Heat transfer models for single-track and three-dimensional droplet-on-demand fabrication under forced vibration were established. Through a combination of experimental investigation and numerical simulation, the evolution of heat transfer and thermal accumulation during the forming process was revealed, and the regulatory mechanisms of process parameters on thermal behavior and forming quality were elucidated. Quantitative analyses were performed to evaluate the effects of substrate temperature, printing speed, and jetting frequency on thermal input and part quality. The results demonstrate that the ratio of thermal to mass input in the molten pool is a key factor governing forming performance. Increasing substrate temperature and jetting frequency elevates the molten pool temperature and promotes complete droplet fusion, thereby enhancing the mechanical properties of the fabricated parts.

(6) Aluminum–silicon alloy was employed as the feedstock to conduct water-hammer-driven droplet-on-demand ejection and fabrication experiments. The influence of process parameters on forming uniformity and interlayer bonding quality was systematically investigated. Quantitative analyses were carried out to assess the effects of printing frequency and printing speed on forming stability. The results indicate that increasing printing frequency or reducing printing speed significantly improves forming uniformity and interlayer metallurgical bonding. The proposed method enables stable droplet-on-demand ejection of low-density, high-melting-point metals, and the fabricated parts exhibit favorable mechanical properties and high process stability, demonstrating strong potential for low-cost, high-performance manufacturing applications.

This study systematically investigates water-hammer-driven droplet-on-demand metal

additive manufacturing through integrated theoretical analysis and process-level experimentation, establishing a comprehensive understanding of the underlying mechanisms and a coherent methodological framework. The present work provides a solid theoretical and technical foundation for the further development and engineering application of this technology.

Key words: Water-hammer effect; Metal additive manufacturing; On-demand metal droplet jetting; Droplet deposition; Numerical simulation