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博士学位论文

航发单晶涡轮叶片气膜孔 放电-电解复合加工技术研究

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**Research on electrochemical discharge
drilling for film cooling hole of aero-engine
turbine single crystal blade**

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摘 要

高压涡轮是航空发动机的三大核心部件之一，其工作在高温、高压的极端环境中，承受着热载荷、离心力和气动力的多重作用。对于高压涡轮叶片，除了采用镍基单晶等高熔点、高强度材料外，气膜冷却技术也得到了广泛应用。在高压涡轮叶片表面分布着上百个微小孔结构，涡轮叶片可以通过铸造的方式批量成型，但其上的气膜孔只能通过后续的加工方法制造。气膜孔孔径小、数量多、加工质量要求高，表面不允许存在微裂纹与重铸层等缺陷。当前，诸如此类气膜孔的加工已成为新机研制的瓶颈问题之一。

目前，气膜孔主流的加工方式包括电火花高速穿孔加工、激光加工与电液束加工，但其均无法在高效加工的同时，实现无重铸层的微小孔加工。行业对于高效、高质量微小孔加工方法的需求十分迫切，亟待开展创新的加工方法研究。本校创新性地提出了放电-电解复合加工技术，该技术结合了电火花穿孔的高效性与电解加工无重铸层的特点。研究发现，火花放电和电化学溶解作用在空间上存在明显的区域性，为实现无重铸层加工提供了依据，表明该技术极有可能应用于难加工材料的微小孔结构制造。然而，在前期的研究中存在着火花放电机理不明晰、小孔加工表面完整性待提升等问题。本文深入研究了复合加工机理，通过关键技术的突破，进一步提高了微小孔的加工效率与表面完整性，解决了重铸层残留、表面杂散腐蚀等问题，并完成复合加工装备搭建，初步实现了无重铸层要求的新型航空发动机单晶涡轮叶片气膜孔的高效、高质量加工。

本文的主要研究内容包括以下几个方面：

(1) 阐明了低电导率溶液中的火花放电机理，深入分析了火花放电与电化学溶解的耦合规律，在国际上首次建立了复合加工的成形仿真预测模型。首先，通过高速摄像的观测表明，在高速内冲液环境下，在工具电极表面上未见明显气膜，低电导率溶液下的放电更接近于电火花加工的液相放电，而非气膜放电。通过波形的分析，量化了复合加工中电解与火花放电的占比，统计了各电导率下极间的阻抗分布，可认为在放电点周围的微观尺度上放电和电解是交替发生的。基于上述机理分析的相关结论，采用生死单元法，首次将离散的火花放电与连续的电化学溶解相结合，最终建立了放电-电解复合加工的仿真预测模型。该模型有助于掌握复合加工的成形规律，实现了对加工过程与结果的预测，为实际加工提供指导。

(2) 掌握了镍基单晶基体及其重铸层的电化学溶解特性，首次深入明晰了重铸层的溶解形貌演变规律。首先，揭示了镍基单晶基体与重铸层的结构，镍基单晶基体包含 γ/γ' 两相，而对于重铸层仅残留 γ 相。重铸层表面凹凸不平且元素分布不均，凸起处的熔滴主要为金属氧化物。随后，通过电化学测试分析，发现重铸层表面的钝化膜比基体表面的钝化膜更稳定、耐腐蚀性更高，其对材料的保护作用更强。最后，掌握了镍基单晶基体及其重铸层的材料去除过程，对于重铸层表面，电化学溶解优先发生在放电凹坑中，凸起熔滴主要以机械脱落的形式去除。对

于基体表面， γ 相优先去除，而 γ' 相后去除。

(3) 提出了电容增益的放电-电解复合加工方法，通过在加工间隙两端并联电容的方式，提升了气膜孔的加工效率。首先，通过波形仿真与电路分析，从理论层面阐明了电容对于火花放电过程与电化学溶解过程的影响。随后，针对电容大小进行了单因素试验，分析了电容对放电峰值电流、加工效率、电极损耗、孔径以及重铸层去除情况的影响，并与电火花加工进行了对比。最终优选电容值为 680 nF，2 mm 厚、0.4 mm 直径的微小孔不到 7 s 即可完成穿透，加工效率可达到 321 $\mu\text{m/s}$ 。

(4) 搭建了复合加工的穿透检测系统，并优化了加工进给模式，提升了复合加工穿孔的稳定性，确保了重铸层的有效去除。首先，提出了一种基于平均电压方差信号的穿透检测判断方法，优选了穿透检测系统的关键参数，在不同脉宽与脉间组合下验证了检测系统的适应性。随后，根据穿透检测的信号反馈，在微小孔的进给阶段与底部停顿阶段之间，新增过进给阶段，获得了不同角度下的最佳过进给距离。最后，利用本穿透检测方法，在典型的双层壁结构试板上进行了微小孔加工试验，加工出的斜孔孔壁无重铸层，无对壁损伤。

(5) 提出了低温外部气流辅助的复合加工方法，创新地引入同轴低温气流，减少了孔口的杂散腐蚀。首先，对低温抑制杂散腐蚀的机理进行了研究，发现溶液电导率与环境温度呈现非线性的变化趋势。低温环境中，材料具有更低的钝化电流与分解电位，并且电化学反应中的电荷转移过程将受到限制，从而达到保护非加工表面的目标。随后，采用多物理场耦合仿真，获得了低温外部气流辅助下的气液、温度与电流密度分布。仿真结果表明，外部低温气流可吹散工件表面覆盖的工作液，降低孔口表面温度，最终降低了工件表面的电流密度。最后，开展了低温气流辅助加工试验，结果显示低温气流辅助下小孔锥度与相对杂散腐蚀面积相较于常温气流辅助可分别下降 35% 与 23%。

(6) 针对放电-电解复合加工特点及镍基单晶气膜孔的加工需求，完成了复合加工装备搭建。结合电容增益加工方案和穿透检测技术，采用放电-电解复合加工方法，在多件高压涡轮叶片实物上，开展了实际气膜孔的加工试验。经检测与分析，各项加工结果均满足技术要求，气膜孔的单孔加工时间在 25 s 内（约 5 mm 孔深），各尺寸微小孔出口直径公差在 +0.05 mm 范围内，孔口无毛刺、无锐边并自动形成一定倒圆，叶片表面少杂散腐蚀。叶片内部无对壁损伤与点蚀，孔壁无重铸层、无裂纹，初步实现了航空发动机镍基单晶高压涡轮叶片气膜孔高效、高质量的加工。

关键词：放电-电解复合加工，气膜冷却孔，镍基单晶高温合金，涡轮叶片，电火花加工，电解加工。

ABSTRACT

The high-pressure turbine stands as one of the three essential components of an aero-engine, functioning under extreme conditions of high temperature and pressure, and is subjected to thermal, centrifugal, and aerodynamic forces. For high-pressure turbine blades, besides using high-melting-point, high-strength materials like Ni-based single crystal superalloys, film cooling technology is also crucial to ensure smooth blade operation. Hundreds of tiny film cooling holes are distributed on the surface of the blade. High-pressure turbine blades can be mass-produced through casting, but the film cooling holes must be manufactured using subsequent machining methods. These film cooling holes have small diameters, are numerous in quantity, and have high quality requirements, with no tolerance for defects like micro-cracks or recast layers on the surface. Currently, the efficient and high-quality manufacturing of such film cooling holes has become a significant bottleneck in the development of aero-engine.

Currently, the primary methods for machining film cooling holes comprise electrical discharge machining (EDM), laser machining (LM), and electrochemical machining (ECM). Nevertheless, these techniques encounter challenges in effectively balancing the removal of recast layers while maintaining high efficiency. The industry has an urgent need for high-quality and efficient manufacturing methods for film cooling holes, necessitating research into innovative machining approaches. Previously, our school innovatively proposed electrochemical discharge machining (ECDM), combining the high efficiency of EDM with the zero recast layer characteristics of ECM. The study identifies distinct spatial regions of discharge and electrochemical dissolution, providing a basis for realizing no recast layer machining, and initially confirms the feasibility and effectiveness of the method. This technology exhibits significant promise for enhancing the manufacturing of intricate components with high performance. However, there are problems in the previous research, such as the spark discharge mechanism is not clear, and the surface integrity of hole machining needs to be improved. This study aims to improve the theoretical foundation of ECDM, further solve the problems of residual recast layer and surface stray corrosion, enhance the surface integrity of small holes, and find ways to improve the machining efficiency. Develop high-precision machine equipment and finalize the manufacture of typical components, enabling the realization of high-efficiency and quality machining of film cooling holes. These advancements will offer vital support for hole manufacturing in aero-engines.

The research consists of the following sections:

- (1) The mechanism of spark discharge in low conductivity solutions is elucidated. The coupled

process of spark discharge and electrochemical dissolution is deeply analyzed. A molding simulation prediction model for composite machining is established for the first time. Initially, analysis through high-speed photography indicates that under high-speed internal flushing conditions, there are no discernible residual bubbles between the electrodes, and no visible air film coats the tool electrode surface. In low-conductivity solutions, the discharge process is closer to liquid-phase discharge in pure EDM rather than film discharge. Waveform analysis reveals the typical characteristics of ECDM, quantifies the proportion of EDM and ECM, and statistically analyzes the impedance at various conductivities, suggesting that discharge and electrolysis occur alternately at a microscopic scale. Drawing insights from the mechanism analysis, discrete spark discharge is integrated with continuous electrochemical dissolution for the first time, leading to the formulation of an ECDM simulation model. This model accurately predicts recast layer distribution and hole diameters, aiding in determining the optimal bottom-holding time.

(2) The electrochemical dissolution characteristics and forming rules of the Ni-based single crystal superalloy matrix and its recast layer are studied for the first time. The evolution of the dissolution morphology of the recast layer is clarified. Initially, the structure of the Ni-based single crystal matrix and the recast layer is revealed. The Ni-based single crystal matrix contains γ/γ' phases, whereas only the γ phase remains in the recast layer. The recast layer surface is uneven, and the distribution of elements is non-uniform, with protruding droplets mainly comprising metal oxides. The passivation film on the recast layer surface is more stable and provides stronger material protection compared to the matrix surface. Ultimately, the material removal process of the Ni-based single crystal superalloy matrix and its recast layer is elucidated. For the recast layer, electrochemical dissolution predominantly takes place in the discharge craters, while the protruding oxide droplets are primarily eliminated through mechanical detachment. For the matrix, the γ phase is preferentially eradicated before the γ' phase

(3) A capacitance-enhanced discharge-electrolysis composite machining method is proposed to improve the machining efficiency of the film cooling holes by connecting capacitors in parallel at both ends of the machining gap. First, an equivalent circuit model is developed to theoretically analyze the impact of capacitance on spark discharge and electrochemical dissolution processes. Then, a one-factor experiment based on varying capacitance values is conducted to analyze peak discharge current, machining efficiency, electrode wear, hole size, and recast layer removal at different capacitances. The optimal capacitance is determined to be 680 nF, achieving a processing efficiency of 321 $\mu\text{m/s}$. With this setup, a small hole with a 2 mm thickness and 0.4 mm diameter can be drilled in under 7 seconds.

(4) A penetration detection system is established, and the machining feed mode is optimized, to

improve the stability of ECDM perforations and ensure the effective removal of recast layers. Initially, a penetration detection method based on the variance of average voltage is proposed, with key parameters of the detection system carefully selected. The stability of the detection system is verified under different pulse width and interval combinations. Subsequently, based on feedback from penetration detection, an additional overfeeding stage is introduced between the drilling and bottom-holding stages. Processing parameters for the overfeeding stage are optimized at different hole angles. Utilizing this penetration detection system, small hole machining experiments are carried out on a double-wall structure, demonstrating no recast layer and no corrosion traces on the backside.

(5) A low-temperature external airflow-assisted ECDM machining method is proposed to reduce stray corrosion in the orifice by the introduction of coaxial low-temperature airflow. First, the study of low-temperature electrochemical dissolution characteristics shows that the solution conductivity has a nonlinear relationship with the ambient temperature. Materials exhibit lower passivation current and decomposition potential in low-temperature environments, with the charge transfer process in electrochemical reactions being restricted, achieving the goal of protecting the surface. Then, through multi-physics field coupling simulation analysis, the distribution of gas/liquid, temperature, and current density under low-temperature external airflow assistance is obtained. The external low-temperature airflow disperses the electrolyte covering the workpiece surface, reducing the surface temperature near the entrance, and ultimately lowering the current density of the workpiece surface. Experimental studies on low-temperature airflow-assisted machining exhibit a 35% decrease in taper and a 23% reduction in stray corrosion area compared to ordinary temperature airflow.

(6) Combined with the characteristics of ECDM and the processing requirements of film cooling holes, a composite processing equipment is developed. Building upon the key technology research from the preceding sections, film cooling holes are manufactured by ECDM on turbine blades. Test results indicate that specifications meet technical requirements, with a single 5 mm depth hole completed in 25 s, the through-hole diameter within a 0.05 mm tolerance, no burrs or stray corrosion, a smooth orifice, and automatic chamfer formation, absence of wall damage or pitting corrosion inside the blade and no recast layer or cracks on the hole wall. This achievement realizes high-quality and efficient manufacturing of film cooling holes on Ni-based single crystal superalloys for turbine blades.

Keywords: Electrochemical discharge machining (ECDM), Film cooling hole, Ni-based single crystal superalloy, Turbine blade, Electrochemical Discharge Machining (EDM), Electrochemical Machining (ECM)