中图分类号：*****

单位代码：*****

学　　号：*****

博士学位论文

Doctoral Dissertation of XX

绿色高效仰视电火花铣削技术及应用基础研究

Fundamental Research on Green High-Efficiency and Upward Electrical Discharge Milling and its Application

学科专业：**机械工程**

研究方向：**机械电子工程**

作者姓名：*****

指导教师：*****　**教授**

二〇二三年五月

Fundamental Research on Green High-Efficiency and Upward Electrical Discharge Milling and its Application

A Dissertation Submitted for the Degree of Doctor of Philosophy

Candidate：***

Supervisor：Prof. ***

摘　要

机械铣削是机械制造领域应用最广的一种加工方法，它采用铣刀“以硬克软”的方式去除工件材料，为机械制造业的发展和科技进步做出了重要贡献。然而，机械铣削难以加工应用领域日益广泛的高温合金、钛合金、金属基复合材料和金属陶瓷等难切削材料，其存在的突出问题是刀具损耗大、加工效率低和成本高。电火花铣削不受被加工材料的强度和硬度等影响，可实现“以柔克刚”，具备解决难切削材料及其复杂结构件加工难题的潜质。但因其加工生产率低这一致命缺陷，仅在微小构件或宏观构件的微观结构加工中获得较好应用。如何提高电火花铣削的加工效率，以促进其应用范围快速扩大，是当今特种加工领域一个极为重要的研究课题。因此，本文选定“绿色高效仰视电火花铣削技术及应用基础研究”作为研究课题，具有重要的理论意义和工程应用价值。本文围绕此课题开展了深入系统的研究工作，并取得了一些具有重要创新性的理论和技术成果。

(1) 原创研发出了绿色高效仰视电火花铣削技术，该技术采用工具电极面向工件向上仰视加工、超强能场电火花和混气水加压冲注，实现了绿色高效电火花铣削。对绿色高效仰视电火花铣削技术和传统的俯视加工技术的加工效率、电极相对损耗率、放电状态、工件加工表面微观形貌、加工表面重铸层结构和工件加工表面成分等进行了对比实验研究。研究结果表明，绿色高效仰视电火花铣削技术具有加工效率高、工具电极相对损耗率低、放电稳定性好、工件加工表面质量高和表面重铸层薄等优点。

(2) 研究揭示了混气水中绿色高效仰视电火花铣削的电火花击穿放电机理，研究发现，在去离子水中混入微气泡，可以使极间电场的等势面扭曲和电场强度发生畸变，易于放电击穿和产生多点放电，使放电能量分散，有利于提高加工质量。探明了混气水中绿色高效仰视电火花铣削的材料蚀除机理，研究发现，对混气水施加压力，可提高其对电火花放电通道的压缩作用和放电爆炸力，使电火花放电蚀除材料的效率增大；工具电极旋转拖动电火花放电等离子体运动，使单脉冲放电蚀除坑的面积增大，坑深减小。揭示了仰视加工方式下加压混气水介质对加工间隙中蚀除产物排出影响机制，研究发现相比于传统的俯视电火花加工技术，仰视电火花加工技术的加工介质间隙流场分布较均匀，有利于加工间隙中的蚀除产物排出和工作介质的循环更新，可显著提高放电加工稳定性，从而提高加工工艺效果。

(3) 提出了绿色高效仰视电火花铣削自动追优外冲方法，探明了工作介质的外冲方式、工作介质的种类、流量和工艺参数等对绿色高效仰视电火花铣削的加工效率、工具电极相对损耗率、工件加工表面微观结构形貌等的影响规律，依此研制出了绿色高效仰视电火花铣削工作介质自动追优外冲气系统，实现了气体介质外冲方向的自动追优控制，提高了绿色高效仰视电火花铣削的加工效率和表面加工质量，降低了工具电极的损耗。

(4) 提出了绿色高效仰视电火花铣削智能伺服控制方法，构建了绿色高效仰视电火花铣削加工数据集，建立了绿色高效仰视电火花铣削放电状态参数的智能识别分类模型、加工效能评价模型和伺服速度智能在线调控模型，开发出了绿色高效仰视电火花铣削智能伺服控制系统，实现了对伺服速度的智能在线调控，使绿色高效仰视电火花铣削实现了高的加工效率、低的工具电极损耗和高的表面加工质量等的最优加工。

(5) 提出了采用电压闭环反馈和 DC/DC 变换的控制策略，设计高压低能电火花击穿脉冲电路，采用电流闭环反馈和逆变技术等设计放电回路中无限流电阻的低压高能电火花加工脉冲电路，由此研发绿色高能电火花脉冲电源的新方法，并研制出了该电源。采用 EtherCAT 协议研制出了绿色高效仰视电火花铣削数控系统，该系统可实现四轴联动、智能伺服控制、工具电极损耗自动补偿、运行信息数据自动采集等功能；研制出了绿色高效仰视电火花铣削机械系统。在上述研究成果的基础上，研制出了世界首套绿色高效仰视电火花铣削数控机床。

(6) 对绿色高效仰视电火花铣削加工工艺进行了实验研究，首次发现了加工极性与加工电流密度有关的新现象，揭示了混气水工作介质中绿色高效仰视电火花铣削加工极性的变化机制。在其他条件不变情况下，加工极性随着峰值电流的增加，在某一电流临界值处发生变化，即在该电流临界值的前后应选择不同的加工极性，该电流临界值的平方与工具电极加工面积呈强线性相关。研究揭示了峰值电流、脉冲宽度、脉冲间隔等电参数，以及工具电极转速、混气水工作介质中的水压和气压等非电参数对绿色高效仰视电火花铣削加工工艺效果的影响规律。研究成果为加快该技术的推广应用步伐，奠定了坚实的工艺技术基础。

关键词： 电火花铣削；高能放电；仰视加工；绿色制造；混气水工作介质

Abstract

Mechanical milling is one of the most widely used machining methods in mechanical manufacturing. It uses milling cutters to remove workpiece materials in a "hard-versus-soft" way, making important contributions to the development and technological progress of mechanical manufacturing. However, mechanical milling is unsuitable for processing increasingly widely used difficult-to-cut materials, such as superalloys, titanium alloys, metal-based composite materials, and cermets. The main disadvantages of mechanical milling are severe tool wear, low machining efficiency, and high cost. Electrical discharge milling (ED milling) is not affected by the strength and hardness of the material to be machined so that it can achieve "soft-versus-hard" machining. Therefore, ED milling has the potential to solve the problem of machining difficult-to-cut materials and complex structural parts. However, due to the fatal drawback of low machining productivity, it has only achieved good applications in processing tiny parts or microstructures of macroscopic parts. Thus, it has been an extremely important research topic in non-traditional machining to study how to improve the machining efficiency of ED milling and expand its industrial application areas rapidly.

In this dissertation, the research topic "Fundamental research on green high-efficiency and upward electrical discharge milling and its application" was selected, which has a significant theoretical significance and engineering application value. Based on this topic, this dissertation has achieved some innovative theoretical and technical research results, as follows.

(1) A green and high-efficiency upward ED milling (HU-EDM) technology has been developed, utilizing tool electrode upward feeding, ultra-strong energy field electrical discharge, and mixed gas-water pressure injection, thereby achieving green and efficient ED milling. Comparative experimental studies were conducted on the HU-EDM method and conventional downward milling method in terms of material removal rate (MRR), relative electrode wear rate (REWR), discharge states, microstructure, recast layer structure, and composition of the surface of machined workpieces. The results show that the HU-EDM method has the advantages of high MRR, low REWR, stable discharge condition, good surface quality, and a thin recast layer on the workpiece surface.

(2) The breakdown mechanism of the HU-EDM method in mixed gas-water is investigated. It is found that introducing air microbubbles into deionized water can distort the equipotential surfaces of the interelectrode gap and cause distortion of the electric field intensity, making the breakdown discharge process easier and resulting in multi-point discharge, dispersing discharge energy, and improving machining integrity. The material removal mechanism of HU-EDM in mixed gas-water is elucidated. The results show that applying pressure to mixed gas-water can enhance its compression effect on the discharge channel and improve discharge explosion force, thereby increasing the efficiency of material removal by electrical discharge. The tool electrode rotation induces movement of the plasma discharge channel, enlarging the area of single-pulse discharge removal pits and reducing the pit depth. The impact mechanism of the high-pressure mixed gas-water medium on the discharge process in HU-EDM is revealed. Compared to conventional downward feed processing, the distribution of the gap flow field in HU-EDM is more uniform. This facilitates the discharge of etching products in the machining gap and the renewal of the working medium, which can significantly improve the discharge stability and machining performance.

(3) The external flushing method with automatic optimization flushing directions for HU-EDM is proposed. The influence of the external flushing method, types, flow rates of the working medium, and machining parameters on the MRR, REWR, and microstructure morphology of the machined workpiece surface is explored. Based on this, an automatic control optimization external flushing gas system for HU-EDM is designed, which achieves automatic tracking and optimization of the external flushing gas direction, improves the MRR and surface integrity, and reduces the REWR.

(4) The mathematical models and intelligent servo control system for HU-EDM were constructed, and the intelligent servo control strategy for HU-EDM was proposed. A dataset of discharge states in HU-EDM was constructed using a large amount of experimental data. The intelligent identification and classification model for the discharge states, the effectiveness evaluation model, and the intelligent online regulation model of servo speed were established. Based on these models, the intelligent servo control system for HU-EDM was developed, and

the intelligent online control of servo speed was realized. The machining results show that the high MRR, low REWR, and high surface integrity of HU-EDM have been achieved.

(5) The control strategy employing voltage closed-loop feedback and DC/DC conversion was proposed. The high-voltage and low-energy electrical discharge breakdown pulse circuit was designed, and the low-voltage and high-energy electrical discharge machining pulse circuit with no current limiting resistors was designed using current closed-loop feedback and inversion technology. Based on this, a developing method for the pulse power supply of HU-EDM was proposed, and the pulse power supply was developed. The CNC system of HU-EDM was developed using EtherCAT protocol, which can achieve four-axis linkage, intelligent servo control, automatic compensation of tool electrode wear, and automatic collection of running data. The mechanical system for HU-EDM was developed. Based on the above results, the HU-EDM CNC machine tool was developed for the first time in the world.

(6) Experimental studies were conducted on the proposed HU-EDM method. The new phenomenon that the machining polarity was related to the machining current density was discovered. Under the same machining conditions, the machining polarity changed as the peak current at the critical point increased, and different machining polarities should be selected before and after the critical point. Further research found a strong linear correlation between the square of peak current at the critical point and the tool electrode machining area. The influence law of electrical parameters, including peak current, pulse width, and pulse interval, and non-electrical parameters, including tool electrode rotation speed, water pressure, and air pressure in the mixed gas-water working medium on the machining performance, were revealed. The results have laid a solid technological foundation for accelerating the pace of popularization and industrial application of HU-EDM.

Key words: Electrical discharge milling; High energy discharge; Upward machining; Green manufacturing; Foam-water working medium