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碩士學位論文

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電化學刷磨複合加工於304不鏽鋼之動力學分析與表面改質

Analysis of Chattering Dynamics and Surface Modifications in Hybrid Electrochemical Brushing of 304 Stainless Steel

研 究 生： 鍾佳峻

指導教授：郭俊良 博士

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摘要

電化學加工使用電能與化學能，對加工表面不產生熱與接觸應力，因而廣泛應用於難切削材料與高表面精度之實務。雖然如此，電化學加工之陽極溶解常因低效率，使得加工表面產生氧化及鈍化反應，而生成陶瓷結構薄膜之不良導體，進而阻礙汲取電流，造成陽極溶解加工中斷。因此，本研究設計一新型複合式電化學刷磨電極機構，透過有限元素之模態分析方法，從複合式陶瓷刷電極之振動頻率響應結果而計算模態參數，並推導理論之穩態顫振圖做為比較之基礎。實驗工作則以理論材料移除率與穩態顫振區間，來設計參數區間，使用極間電壓 15–25 V 耦合研磨轉速 800–1600 rpm 與進給率 0.014–0.35 mm/rev 進行實驗。複合式電化學刷磨之目標工作物為 304 不鏽鋼，觀測指標為材料移除率、汲取電流、統計計量之表面粗糙度(S_a, R_{ku}, R_{sk})，加工表面形貌、殘留應力、奈米等級壓硬度，與參數間之物理效應。最後，透過統計檢定方法分析刷磨加工與複合加工之參數效應、交互作用、統計顯著性與參數影響力。研究結果顯示，刷磨加工之下壓深度與下壓力為線性區間，穩態顫振圖建議降低顫振之參數組合為，高研磨 1600 rpm 轉速搭配低進給率 0.014 mm/rev，可產生最小粗糙度 131.4 nm。統計檢定顯示，複合加工可提高電化學加工表面峰度值最高 36.1%，同時降低偏度值 73.9%，有助於高負載與滑動之場合。殘留應力分析顯示，複合加工可去除電化學加工形成之鈍化膜，提升表面之壓應力，抑制表面缺陷成長增加疲勞壽命。

關鍵字：電化學刷磨複合加工、陽極溶解加工、陶瓷纖維刷磨加工、有限元素分析、模態分析、穩態顫振圖、表面形貌參數、殘留應力、奈米壓硬度

Abstract

Electrochemical machining utilizing electrical and chemical energy to process surfaces without generating heat or contact stress has been widely used in practical applications involving difficult-to-cut materials and high surface precision. However, the anodic dissolution in electrochemical machining is often problematic due to its low current efficiency, leading to the formation of oxidation and passivation reactions on the processed surface. Moreover, the produced oxide and passive film deteriorate the electrical conductivity and hinder the current drawn and hence interrupt the anodic dissolution process. In this work, a novel hybrid electrochemical brushing process was designed and presented for sustaining the anodic solution process in a steady way. Through finite element methods, the modal analysis has been carried out as well as the modal parameters were calculated based on the vibration frequency and response results of the hybrid electro-chemical brushing process. In the design of experiments, the theoretically derived stability lobe diagram provided a basis for determinations of preferable parametric intervals on the material removal rate and the confirmation of the steady state from chattering. In the validation experiment, the hybrid electrochemical brushing was carried out with the open voltage of 15–25 V, coupling with spindle speeds of 800–1600 rpm and feed rates of 0.014–0.35 mm/rev, on the target workpiece of 304 stainless steel. The objectives were the material removal rate, drawn current, statistical surface roughness (S_a, R_{ku}, R_{sk}), brushed surface

topography, residual stress, nano-indentation of surface hardness, and physical effects associated with the parameters. Lastly, statistical analysis methods were employed to analyze the parameter effects, interactions, statistical significance, and parametric contributions in the hybrid process. Analysis of residual stress, surface roughness and alternation of nano-hardness on the machined surface in electrochemical brushing process, were reported and discussed in detail.

Keywords: Hybrid electrochemical brushing, Anodic dissolution machining, Ceramic fiber brushing, Finite element analysis, Modal analysis, Stability lobe diagram, Surface topography, Residual stress, Nano-indented hardness