博 士 学 位 论 文

CFRP/铝合金叠层结构一体化切削理论与钻孔技术研究

Cutting Mechanism and Drilling Technologies for One-shot Machining of CFRP/Al Stacks

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摘 要

碳纤维增强树脂基复合材料（Carbon Fiber Reinforced Plastic，CFRP）和铝合金是航空航天、轨道交通等领域主要的结构材料，CFRP 和铝合金零件在连接装配时形成了大量的 CFRP/铝合金叠层结构。CFRP/铝合金叠层结构主要通过螺栓或铆钉连接，故需对其加工大量连接孔。同时，为保证精度并提高效率，工程中多在装配工位上对 CFRP/铝合金叠层结构进行一体化钻削制孔。但 CFRP 和铝合金的物理化学属性和机械加工性能差异显著，且两者一体化加工时相互影响（CFRP 挤压铝合金、铝合金切屑划伤 CFRP），难以同时实现 CFRP 低损伤去除和铝合金断屑排出，存在 CFRP 切削质量差、一体化制孔效率低和刀具寿命短等问题。为此，本文研究了叠层结构界面区域 CFRP 的去除行为，提出了满足 CFRP 低损伤切削约束的铝合金切屑断裂方法，研制了可同时实现 CFRP 低损伤去除和铝合金有效断屑的钻削刀具，在此基础上，考虑叠层厚度影响对研制刀具进行了工艺参数匹配，开发了适用于研制刀具的金刚石局部镶嵌方式，提出了 CFRP/铝合金叠层结构一体化钻削制孔关键技术。主要工作和结论如下：

(1) 建立了考虑周围材料约束和各向异性的 CFRP 斜角切削解析模型，求解得到了 CFRP 斜角切削时的切削力，实现了 CFRP 直角和斜角切削时切削力的准确预测，最大相对误差小于 15%。在此基础上，考虑铝合金对叠层结构界面区域 CFRP 的支撑作用，实现了叠层结构界面区域 CFRP 去除过程的解析表征，计算了切削宽度和刃倾角等铝合金切屑断裂敏感参数对界面区域 CFRP 切削过程和损伤的影响规律，明确了适宜切削深度、小刃倾角、小切削宽度有利于实现 CFRP 的低损伤去除，以 CFRP(T800/X850)/铝合金(7075-T6)叠层结构为例，计算了刃倾角临界值和切削深度优选范围，为一体化钻削刀具切削刃角度和加工参数的确定提供指导。

(2) 提出了 CFRP 低损伤参数约束的“复合卷曲”铝合金切屑断裂方法。分析了切屑在斜角切削过程中流动/卷曲行为和断裂条件，建立了铝合金切屑表层应变计算模型，提出了限制铝合金切屑侧向流动的铝合金切屑断裂方法，突破了传统小前角、圆弧前刀面等铝合金断屑方法对刀具的限制，对比实验证明“复合卷曲”断屑方法可在大前角、小切深条件下实现铝合金切屑的有效断裂，验证了此方法对 CFRP/铝合金叠层结构切削的适用性。进一步建立了铝合金切屑“复合卷曲”时表层应变的计算模型，分析了材料属性和切削参数对切屑表层应变和断裂的影响，发现适当切削宽度、大刃倾角和小挡面前角利于切屑断裂，给出了挡面角度的优选范围为 0°到 90°，为实现 CFRP/铝合金叠层结构一体化钻削时铝合金切屑有效断裂提供了理论指导。

(3) 以 CFRP 低损伤去除和铝合金复合卷曲断屑的结论为指导，发明了适用于

CFRP/铝合金叠层结构一体化钻削的阶梯竖刃刀具，以高强度 T800 级 CFRP(X850)和难断屑铝合金(2024-T4)组成的叠层结构进行了效果验证，实验结果证明：阶梯竖刃刀具既可低损伤去除 CFRP，又能不借助附加工艺实现铝合金有效断屑，大幅提高了 CFRP 的入口和孔壁质量。在此基础上，以改进的 CFRP 损伤和铝合金毛刺视觉量化方法、以及叠层孔径评价指标为基础，研究了材料厚度和切削参数对阶梯竖刃刀具钻削质量的影响规律，揭示了热/机械共同作用下阶梯竖刃刀具钻削缺陷的形成机制，确定了阶梯竖刃刀具钻削不同厚度的 CFRP(T800/X850)/铝合金(7050-T7451)叠层结构的适宜工艺参数，验证了阶梯竖刃刀具对 CFRP/铝合金叠层结构的普适性。

(4) 开发了考虑阶梯竖刃刀具磨损特性的金刚石局部镶嵌方式。分析了阶梯竖刃刀具钻削 CFRP/铝合金叠层结构时不同切削刃的磨损形态，结果表明：第一主切削刃、副切削刃和竖刃主要呈铝合金粘结磨损，而第二主切削刃磨损从铝合金粘结磨损向 CFRP 研磨过渡。同时，量化了第二主切削刃形貌随制孔数目的变化规律，发现阶梯竖刃刀具钻削 CFRP/铝合金叠层结构时，后刀面磨损宽度 VB 呈单调增加，而切削刃钝圆半径会因重新刃磨呈波动上升。通过对比切削刃的磨损状态和磨损量，明确第二主切削刃为主要磨损位置且轴向磨损长度与竖刃前刀面长度近似相等。据此，开发了适用于阶梯竖刃刀具的金刚石局部镶嵌方式，与整体硬质合金刀具相比，后刀面磨损宽度 VB 降低近 70%，同时大幅降低了 CFRP 损伤、铝合金毛刺以及孔径偏差。

研究成果已在航空航天装备中典型 CFRP/铝合金叠层结构件中完成了效果验证和批量化应用，满足了成飞、沈飞等企业关键构件的制造亟需。

关键词：CFRP/铝合金叠层结构；一体化钻孔；损伤抑制；刀具结构

ABSTRACT

Carbon Fiber Reinforced Plastic (CFRP) and Aluminium alloys (Al) are considered as excellent structural materials in aerospace and rail transport, leading to numerous CFRP/Al stacks during the assembly process. The CFRP/Al stacks are fastened by bolts or rivets primarily. Then, a large number of holes have to be drilled in CFRP/Al stacks. Drilling operation on the CFRP/Al stack is expected to be completed in a single operation to increase productivity and accuracy. However, the significant differences in mechanical and physical properties between CFRP and Al, as well as the effects between the Al chip and CFRP in cutting process, bring technical challenges to achieve low damage cutting of CFRP and effective chip breaking of Al simultaneously. Thus, the quality, efficiency, and tool life, are required to be further improved. To address these challenges, the cutting mechanism of CFRP in the interface region are investigated, and the breaking mechanism of the Al chip is theoretically analyzed. A novel drill is proposed to achieve low-damage drilling CFRP/Al stacks. Further, the drilling parameters are optimized for stacks with different thicknesses, and a localized diamond-filled process for the novel drill is developed based on the wear characteristics. Finally, the key technologies for one-shot drilling of CFRP/Al stack are proposed to meet the engineering requirements. The main research results and conclusions are as follows:

(1) An analytical model for the oblique cutting process of CFRP is established, utilizing the theory of elastic foundation plate and symplectic superposition. This model considers the constraints and anisotropy. The cutting forces during the oblique cutting process of CFRP are obtained, realizing the accurate prediction of cutting forces in orthogonal/oblique cutting processes of CFRP with the maximum relative error of 15%. Accordingly, considering the constrained state of Al on CFRP in the interface region of the stacks, the cutting process of CFRP in the interface region is analytically characterized. Then, the influence of Al chip-breaking sensitive parameters on damage caused by cutting CFRP is systematically investigated. It is clarified that the appropriate cutting depth, small inclination angle, and small cutting width is beneficial for reducing the cutting damage of CFRP. Besides, the critical value of the inclination angle and the preferred cutting depth range are obtained according to the analytical model, when cutting (T800/X850)/Al (7075-T6) stacks. These results provide reference for designing cutting-edge angles and drilling parameters.

(2) The compound-curl method is proposed for breaking Al chip within low damage cutting parameters of CFRP. The flow and curl behavior, as well as the broken conditions, of Al chips in the oblique cutting process, are analyzed. A model for calculating the surface strains of Al chips is established. Subsequently, a method is proposed for breaking Al chip by limiting the side flow of Al chips. The effectiveness of the compound-curl method for the CFRP/Al

stack is confirmed through comparative experiments with conventional Al chip-breaking methods, such as using a small rake angle and a rounded front face. The results show that the Al chip can be effectively broken using the compound-curl method under cutting conditions with a large rake angle and a small cut depth. A calculation model for the surface strain of the Al chip within the compound-curl method is then established. The model is used to analyze the effects of different maerial properties and cutting parameters on the surface strain and chip breaking. The appropriate cutting width, a large inclination angle, and a small block angle are favorable for breaking Al chip. The optimal range of block angles for designing the chip-breaking structure of a one-shot drill is determined to be from 0° to 90°. The results provide guide for designing the chip-breaking structure of a one-shot drill.

(3) The stepped vertical-edge drill is invented to achieve efficient cutting of CFRP and breaking of Al chip simultaneously, according to the conclusions that a small cutting width and inclination angle are conducive to low-damage cutting of CFRP, and the compound-curl method can break the chip without changing the cutting edge angle. The comparative one-shot drilling experiments are carried out on high-strength T800 CFRP and a hard-to-break chip of 2024-T4 Al to validate the effectiveness of the stepped vertical-edge drill. The experimental results proved that the stepped vertical-edge drill can effectively remove CFRP with low damage and successfully break Al chip without additional processes, which significantly improves the CFRP quality of the entrance and hole wall. Based on improved methods of quantifying CFRP damage, Al burr, and hole diameter indicator, the subsequent effects of CFRP thickness and drilling parameters on drilling quality are comprehensively investigated in the case of the stepped vertical-edge drill. The effects of thermal-mechanical interaction on the drilling defects are elucidated in drilling CFRP/Al stacks. Hence, the appropriate drilling parameters are determined for the stepped vertical-edge drill in the case of drilling CFRP (T800/X850)/Al (7050-T7451) stacks with different thicknesses. The stepped vertical-edge drill provides valuable insights for various engineering applications of CFRP/Al stacks.

(4) A localized diamond-filled process for the stepped vertical-edge drill is expended, taking into consideration of the wear characteristics of which. The wear of the stepped vertical-edge drill with multiple cutting edges is investigated when drilling CFRP/Al stacks. The analysis of the experimental results shows that the major cutting edge, minor cutting edge, and vertical edge are primarily subjected to the main wear mechanism of Al bonding. However, the wear behavior of the secondary cutting edge transitions from Al bonding to CFRP abrasive in the drilling process. Besides, the variation of the secondary cutting edge with the hole number is studied. The results show that the edge radius increased in a fluctuating manner with the number of holes due to the re-sharpening, while the flank wear VB increased consistently in the continuous drilling process. The secondary cutting edge is considered as the primary wear

edge, and the axial wear length is approximately equal to the length of the vertical edge, by comparing the wear process of different cutting edges. Then, a localized diamond-filled process for the stepped vertical-edge drill is developed. The comparison experiments show that the flank wear VB width is decreased by nearly 70% compared with the carbide drill. Besides, CFRP damages, Al burr, and diameter deviation are significantly reduced in drilling CFRP/Al stacks.

In summary, cutting mechanism and drilling technologies for one-shot machining of CFRP/Al stacks are developed, which have been validated through engineering applications of the aerospace industry. The results meet the urgent needs of Chengfei, Shenfei and other airlines enterprises for manufacturing key components.

Key Words：CFRP/Al Stacks; One-shot Drilling; Damage Reduction; Drill Structure.