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工件超声振动的镍基高温合金叶片榫齿高效磨削技术研究

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High efficiency grinding technology of nickel-based superalloy blade root based on workpiece ultrasonic vibration

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摘 要

铸造镍基高温合金涡轮叶片是航空发动机的核心部件，决定了发动机的动力性能。榫齿是涡轮叶片的设计基准，起着定位和安装的重要作用，榫齿加工质量是航空发动机动力性能能否保障的重要制约因素。磨削是榫齿加工的关键工序，然而传统磨削中由于磨粒与工件接触长度较长，导致了材料去除率低、砂轮磨损严重的瓶颈问题，严重制约了叶片榫齿加工效率的提升。

有鉴于此，论文提出开展工件超声振动的镍基高温合金叶片榫齿高效磨削技术研究，通过超声振动磨粒断续切削降低磨粒与工件的接触长度，突破了传统磨削高温合金材料去除率低的难题，实现了镍基高温合金叶片榫齿的高效磨削加工。主要创新工作及成果如下：

（1）采用表观弹性法建立了叶片榫齿超声振动平台结构参数与谐振频率的关系，揭示了均布多孔结构对超声振动平台振动特性的影响机制，发明了“小尺寸大波长”的叶片榫齿超声振动辅助磨削系统。结果表明，相比传统无孔超声振动平台，多孔超声振动平台尺寸减小了 52%，振幅提升了 67%；叶片榫齿超声振动辅助磨削系统的谐振频率为 19.3 kHz，榫齿位置最大超声振幅为 10 μm，为叶片榫齿超声振动辅助高效精密磨削提供了装备支持。

（2）基于磨粒与工件的相对运动关系构建了超声振动辅助磨削磨粒断续切削行为模型，揭示了超声-机械复合能场作用对磨削力和磨削温度的影响，阐明了“短接触长分离”的超声振动辅助磨削材料去除机制。研究发现，相比于传统磨削，超声振动辅助磨削的磨粒与工件接触长度减小了 58%，磨削力和磨削温度分别降低了 35%和 34%，工件表面形貌主要为周期性分布的短磨痕，提高了加工表面均匀性，解决了传统方法磨削镍基高温合金叶片榫齿易烧伤的难题。

（3）依据磨粒断续切削行为特点构建了超声振动辅助磨削的刚玉砂轮径向磨损量数学模型，探明了榫齿轮廓特征对砂轮磨损的影响规律，揭示了“微破碎高耐磨”的超声振动辅助磨削砂轮磨损机制。结果显示，超声振动辅助磨削通过磨粒的微破碎避免了磨粒脱落、大块破碎等严重影响叶片榫齿加工精度的砂轮磨损行为；相比于传统磨削，超声振动辅助磨削具有更长久的稳定磨损阶段，解决了传统磨削镍基高温合金叶片榫齿的刚玉砂轮寿命短难题。

（4）考虑多颗磨粒运动轨迹叠加现象构建了超声振动辅助磨削材料部分去除模型，获得了磨粒断续切削行为发生的临界超声振幅与频率，提出了超声振动辅助磨削工艺参数调控策略，完成了生产现场的 K4002 铸造镍基高温合金叶片榫齿超声振动辅助磨削技术验证，实现了“高效率高品质”加工。结果表明，相比于传统磨削，超声振动辅助磨削的最大材料去除率提升 25%，单个叶片榫齿的加工用时缩短 24%，突破了磨削效率的提升难题。

论文成果对于创新发展铸造镍基高温合金涡轮叶片榫齿的先进磨削加工技术，实现高推重比航空发动机涡轮叶片快速研制和高效批产具有重要意义。

关键词： 铸造镍基高温合金，涡轮叶片榫齿，成形磨削，超声振动辅助磨削，材料去除机理，砂轮磨损行为

ABSTRACT

Being a key part of aero-engine, cast nickel-based superalloy turbine blade determines the dynamic performance of aero-engine. The root is the design basis of the turbine blade and plays an important role in locating and assembling. The machining quality of blade root is an important factor to ensure the excellent service performance of aero-engine. Grinding is a key machining method of blade root. However, due to the long contact length between abrasive grain and workpiece, the conventional grinding (CG) is faced with the bottleneck problems of low material removal rate and serious grinding wheel wear. This phenomenon seriously reduces the machining efficiency.

To solve the problems, a workpiece ultrasonic vibration-assisted grinding technology (UVAG) is proposed for high efficiency machining of blade root. The contact length between abrasive grain and workpiece is reduced by the intermittent cutting in UVAG, which promotes an increase in the material removal rate. High efficiency grinding of superallogy blade root is finally realized. The main work and achievements are as follows:

(1) An UVAG device with porous structure was designed according to the apparent elastic method. The relationship between the structure parameters and vibration characteristics of UVAG device was revealed. An UVAG device with small device and large wavelength for grinding blade root was developed. Results indicate that the size of the developed UVAG device is 52% reduced and the vibration amplitude is 67% increased by the porous structure. The resonant frequency of UVAG device is 19.3 kHz with the maximum vibration amplitude of 10 μm in the blade root position. The designed UVAG device provides equipment support for the high efficiency grinding of the blade root.

(2) A model of intemittent cutting behavior was established based on the relative kinematic analysis between abrasive grain and workpiece. The influence of ultrasonic-mechanical combined energy field on the grinding removal process of superalloy was investigated. The material removal mechanism in UVAG was revealed as short contact and long separation. Results indicate that the contact length between abrasive grain and workpiece is reduced by 58%, the grinding force and temperature are reduced by 35 and 34% in UVAG, respectively. The periodic distributed short grinding trace is generated on the UVAG machined surface, which improves the homogeneity of workpiece surface morphology. The problem of easy surface burnout in CG is solved.

(3) Based on the characteristics of intermittent cutting behavior, a mathematical model of alumina abrasive wheel radical wear in UVAG was established. The influence of blade root profile on the grinding wheel wear was investigated. The grinding wheel wear mechanism in UVAG was revealed as micro-fracture and long service time. Results indicate that UVAG promotes the micro-fracture of abrasive grain and improves the abrasive grain self-sharpness ability, avoiding many serious wear

behaviors such as abrasive grain pullout and block breaking. The serious wear behavior greatly reduced the machining accuracy. Finally, the problem of short service life of alumina abrasive wheel is solved.

(4) A material probability removal model was established for the critical vibration amplitude and frequency in UVAG through considering the superposition of many grinding trajectories. The critical vibration amplitude and frequency of the intermittent cutting behavior were obtained. A process parameter optimization strategy for high efficiency UVAG was proposed. The technical verification of UVAG K4002 cast nickel-based superalloy blade root was completed in the factory. The blade root grinding operation with high efficiency and high quality was realized. Compared with CG, UVAG increases the maximum material removal rate by 25% and reduces the blade root machining time by 24%. The difficulty to improve the grinding efficiency is solved.

The achievements of this research work are important significance for developing a new advanced machining technology for cast superalloy aero-engine blade root, accelerating the rapid development and high efficiency batch production of the high thrust-to-weight ratio aero-engine turbine blade.

Keywords: Cast nickel-based superalloy, turbine blade root, profile grinding, ultrasonic vibration-assisted grinding, material removal mechanism, alumina wheel wear behavior