微纳沟槽光学衍射调控与超精密飞切加工研究

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Study on the Optical Diffraction Regulation and Ultra-precision Fly Cutting of Micro-nano Grooves

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摘要

微纳沟槽属于典型的衍射光栅结构，通过设计微纳沟槽形貌与周期尺寸可以调控光学衍射效率。尺度在亚微米级的单级微纳结构、两级结构和多级结构构成的衍射光学元件(DOE)可以通过衍射性能调控具备光信息处理能力，在高饱和度显示、结构色防伪和光芯片领域中发挥重要作用。为实现 DOE 衍射调控和应用，其关键是突破微纳结构光学衍射设计与超精密加工技术。然而，现有的针对微纳结构的衍射分析方法无法适用于复杂形貌的微纳结构，微纳结构非自由切削材料去除机理、加工变形机理和加工变形尺度效应不明，复杂微纳结构加工手段缺乏，尚不能支撑微纳结构的光学应用设计、超精密飞切加工和形性一体化调控技术。本论文以微纳沟槽为研究对象，针对微纳沟槽光学衍射设计难题、微纳沟槽非自由切削加工变形控制难题以及复杂沟槽超精密高效加工难题，系统性地开展了微纳沟槽衍射分析与光学设计、微纳沟槽非自由切削加工理论、超精密飞切加工方法和形性一体化调控研究。本论文将光学衍射和机械加工领域有机结合，主要研究内容和创新性成果如下：

1. 提出了基于相位累加的微纳沟槽光学衍射分析方法，构建了基于时域有限差分法(FDTD)的微纳沟槽光学衍射仿真模型，揭示了锯齿形和 V 形两种微纳沟槽的衍射特性，建立了用于衍射调控的微纳沟槽形状设计理论，设计出具备高衍射效率的微纳沟槽形状。

2. 揭示了非自由切削剪切干涉和排屑干涉机理，基于刃口微元概念提出非自由切削变剪切角模型，构建了非自由切削局部剪切角计算公式，确立了 V 形微纳沟槽非自由切削剪切曲面和切屑截面形状的数学表达；结合非等分剪切区理论和 Johnson-Cook 理论，建立了剪切角与剪切应力的关系；采用切削力微分法，建立了微纳沟槽非自由切削力学模型，揭示了微纳沟槽非自由切削加工变形机理。

3. 建立了单级 V 形微纳沟槽以及两级沟槽切削有限元仿真模型，开展了加工变形尺度效应研究，揭示了微纳沟槽加工变形演变机制和变形规律；通过刃口上节点应力分布规律验证了非自由切削变剪切角模型和微纳沟槽非自由切削力学模型；开展微纳沟槽切削加工试验，验证了单级微纳沟槽和两级沟槽切削过程中的变形理论，确立了单级微纳沟槽、两级沟槽和三级沟槽的加工变形控制策略。

4. 提出了复杂微纳沟槽径向飞切(RFC)加工法，研究了平面轴向进给径向飞切(P-

AFRFC)、伺服辅助轴向进给径向飞切(SA-AFRFC)、平面螺旋进给径向飞切(P-HFRFC)和伺服辅助螺旋进给径向飞切(SA-HFRFC)四种加工模式；构建了多样式微纳沟槽的生成算法，采用数值计算模拟微纳沟槽的生成；在四种 RFC 加工模式下开展了单级微纳沟槽、两级沟槽和三级沟槽的加工试验，验证了 RFC 的复杂微纳沟槽加工能力和表面生成算法的有效性。

5. 开展了单级微纳沟槽、两级沟槽和三级沟槽的光学形性一体化调控研究；通过分析单级微纳沟槽的虹彩衍射特性，建立像素信息和沟槽周期的映射关系，实现结构色单元特征尺寸设计和结构色图像制造；提出通过进给路径调控两级沟槽图案形状的方法，结合第二级微纳沟槽的虹彩效应，实现结构色图案形状-色彩协同调控；基于几何光学理论和衍射光学理论，建立三级沟槽的光学调控仿真模型，优化设计并制造目标三级沟槽，实现了宽光谱衍射增强与光分束功能一体化，推进了微纳沟槽在光学衍射调控方面的应用。

关键词：超精密加工；飞切加工；非自由切削；微纳沟槽；多级结构；光学衍射

Abstract

The micro-nano groove is a typical diffraction grating structure, and the optical diffraction efficiency can be adjusted by designing the shape and period size of the micro-nano groove. Diffractive optical elements (DOEs) composed of single-level micro-nano structures, two-level structures or multi-level structures in the submicron scale, are able to process optical information by regulating the diffraction performance, playing an important role in the fields of high-saturation display, structural color anti-counterfeiting and optical chip. To realize the diffraction regulation and application of DOE, the optical diffraction design theory and ultra-precision machining technology of micro-nano structure need to be improved. However, the existing methods for analyzing diffraction of micro-nano structure are unavailable to micro-nano structures with complex shape. The material removal mechanism, cutting-caused deformation mechanism and deformation scale effect under non-free cutting of micro-nano structure are unclear. There also lacks maching method for micro-nano structures with complex shape. Therefore, the current knowledge fails to support the optical application design, ultra-precision fly cutting and integrated control technology of shape and performance of micro-nano structure. In this paper, micro-nano grooves are taken as the research object, aiming at the challenge in optical diffraction design of micro-nano grooves, deformation control of micro-nano grooves in non-free cutting machining, and ultra-precision and high-efficient machining of complex grooves, a systematic research on micro-nano grooves was carried out. In this paper, the knowledge of optical diffraction and mechanical machining are logically combined. The main research contents and innovative achievements are as follows:

1. A phase accumulation-based optical diffraction analysis method for micro-nano grooves was proposed, and an optical diffraction simulation model of micro-nano grooves was constructed based on the finite-difference time-domain method (FDTD). The diffraction properties of jagged and V-shaped micro-nano grooves were investigated. The theory of micro-nano groove shape design for diffraction regulation was established, and the shape of micro-nano groove with high diffraction efficiency was determined.

2. The mechanism of shearing interference and chip removal interference were revealed.

A non-free cutting material removal model with variable shear angle was proposed based on the concept of infinitesimally-segmenting tool edge, and a formula for calculating the local shear angle of non-free cutting was established. Therefore, the mathematical expression of the shear surface and chip section-profile of the micro-nano groove in non-free cutting was achieved. Combining the unequal shear zone theory and Johnson-Cook theory, the relationship between shear angle and shear stress was established. Sequently, the mechanical model of non-free cutting of micro-nano groove was established via the cutting force differential method, and so the mechanism of cutting-caused deformation was revealed.

3. The cutting models of single-level V-shaped micro-nano grooves and two-level grooves were established by finite element method. The scale effect of cutting-caused deformation of micro-nano grooves was investigated, and the deformation evolution mechanism and deformation law of the micro-nano groove were determined. The variable shear angle model and the mechanical model of non-free cutting were verified by the stress distribution law of the nodes on the tool edge. Micro-nano grooves cutting experiments were carried out to verify the deformation theory during the cutting of single-level micro-nano grooves and two-level grooves. The strategies for controlling the cutting-caused deformation of single-level micro-nano grooves, two-level grooves and three-level grooves were determined.

4. The radial fly cutting method (RFC) for machining complex micro-nano grooves was proposed, and four RFC machining modes were investigated, named the planar axially-feeding radial fly cutting (P-AFRFC), the servo-assisted axially-feeding radial fly cutting (SA-AFRFC), the planar helically-feeding radial fly cutting (P-HFRFC), and the servo-assisted helically-feeding radial fly cutting (SA-HFRFC), respectively. A surface generation algorithm suitable for varieties of micro-nano grooves was is constructed, and the generation of complex micro-nano grooves was simulated by numerical calculation. The machining of single-level micro-nano grooves, two-level grooves and three-level grooves was completed under four RFC machining modes, which verified the capability of RFC and the effectiveness of the surface generation algorithm.

5. The integrated regulation of shape and optical performance of single-level micro-nano grooves, two-level grooves and three-level grooves has been investigated. By analyzing

the iridescent diffraction characteristics of single-level micro-nano grooves, the mapping relationship between pixel information and grooves period was established to realize the design of the structural color unit and the manufacture of the structural color image. A method to regulate the pattern shape of the two-level groove by contolling the feed path was proposed, and the co-regulation of the shape and color of the structural color pattern was realized with the assistance of the iridescent effect of the second-level micro-nano grooves. Based on the theory of geometric optics and diffractive optics, the simulation model of optical regulation of three-level grooves was established. The integration of wide-spectrum diffraction enhancement and optical beam splitting was achieved by optimizing the design and fabricating the target three-level grooves. Therefore, the application of micro-nano grooves in optical diffraction regulation has been promoted.

Keywords: Ultra-precision machining, Fly cutting, Non-free cutting, Micro-nano grooves, Multi-level structures, Optical diffraction