中图分类号：　　　　　　　　　　　　　　　　　　　学校代号：XXXX

UDC：　　　　　　　密级：　　　　　　　　学号：XXXXXX

XXXX 大学博士学位论文

（工学博士）

辊筒模具菲涅尔结构加工及在位测量技术研究

XXX

指导教师姓名、职称：XXX 教授

学科（专业）或领域名称：机械工程

学生所属学院：机电工程学院

答辩委员会主席：XXX 教授

论文答辩日期：2023 年 5 月 25 日

A Dissertation Submitted to XXXX

for the Degree of Doctor

(Doctor of Engineering Science)

Research on machining and on-machine measurement technology of Fresnel lens structure on roller mold

Candidate: XXX

Supervisor: Prof. XXX

May 25,2023

摘要

菲涅尔透镜的聚光光伏 (CPV) 太阳能发电系统可以显著提高光电转换效率。目前，太阳能发电厂通常有几平方公里的面积，这将需要数百亿个菲涅尔透镜。辊对辊(R2R)压印是一种连续大批量制造光学微结构的技术。具有菲涅尔结构的辊筒模具是 R2R 压印工艺中的关键部件。但是，辊筒模具菲涅尔结构加工难度较高，对现有加工技术和机床结构都提出了很高的要求，并且辊筒模具的质量和尺寸大也给模具表面检测技术带来了新的挑战。因此，如何实现大尺寸辊筒模具菲涅尔结构加工及其在位测量成为了菲涅尔透镜大批量制造所面临的难题。

本文对辊筒模具菲涅尔结构的制造流程展开了研究，包括菲涅尔透镜设计及聚光性能模拟分析、辊筒模具菲涅尔结构切削加工方法、辊筒模具菲涅尔结构三维轮廓在位测量以及在位测量误差分离方法。主要研究工作如下：

（1）针对大型辊筒模具径向菲涅尔结构加工的难题，开发了基于 A 轴、C 轴、X 轴和 Z 轴四轴联动的大型辊筒模具径向菲涅尔结构切削加工方法，首次在辊筒机床上实现了径向菲涅尔结构阵列的加工。根据菲涅尔透镜的设计、金刚石刀具几何参数选择以及辊筒尺寸对辊筒模具径向菲涅尔结构加工路径进行规划。分析了金刚石刀尖与机床 A 轴旋转中心对准误差以及辊筒直径测量误差对菲涅尔结构加工产生的影响。

（2）针对高填充性菲涅尔结构阵列加工轨迹不连续的问题，提出了一种圆弧过渡加工方法，首次在辊筒机床上实现了高填充性菲涅尔结构阵列加工。依据聚光性能和填充系数两个评价指标，通过光学仿真软件对高填充性菲涅尔透镜进行优化。修剪径向菲涅尔结构阵列的修剪区域加工容易产生刀具干涉，采用圆弧过渡方法优化了修剪区域刀具加工路径，并进行了刀具半径补偿。通过对菲涅尔结构三维形貌仿真，确定了加工时的每转进给量和刀具圆弧半径大小，对辊筒上环形槽切削加工实验确定了切削参数中的切削速度和切削深度。

（3）针对大型辊筒模具微结构三维轮廓测量的难题，开发了基于位置同步数据采集技术的在位测量系统，并根据辊筒模具微结构特征设计了不同的测量方案。通过对在位测量系统运动误差的分析，得到 Z 轴水平直线度误差对测量结果影响最大。采用高精度的平晶对 Z 轴水平直线度误差重复性进行了测量和误差补偿。针对辊筒模具

径向菲涅尔结构特点，利用等角度与等弧长结合的方法对扫描测量路径进行了优化，提高了在位测量的准确性和效率。

（4）针对大型辊筒机床Z轴导轨水平直线度和主轴径向跳动误差难以补偿的问题，本文开展了其误差分离技术的研究，并提出了基于剪切平台的错位两点法，分离了导轨水平直线度误差和主轴径向跳动误差，来提高在位测量的准确性。对基于剪切平台的错位两点法分离导轨直线度误差和主轴径向跳动误差算法进行了推导。通过仿真分析了机床Z轴定位误差、剪切平台定位误差、C轴定位误差以及光谱测头的噪声对菲涅尔结构截面轮廓重构的影响，分析结果表明其误差影响均在亚微米级别。

（5）开展了辊筒模具菲涅尔结构加工和在位测量实验。通过提出的加工方法对径向菲涅尔结构和高填充性菲涅尔结构进行了加工。采用开发的在位测量系统对菲涅尔结构三维轮廓进行了测量，并将测量结果和理论轮廓进行比较。利用提出的错位两点方法分别对辊筒模具菲涅尔结构轴向和径向截面轮廓进行测量实验，并分离 Z 轴水平直线度和 C 轴径向跳动误差。将在位测量获得的截面轮廓与泰勒 PGI 1240 轮廓仪测量的截面轮廓进行比较，两个结果吻合较好，验证了提出的在位测量方法的准确性。

关键词：辊筒模具；高填充性菲涅尔结构；超精密加工；在位测量；误差分离

ABSTRACT

Concentrating Photovoltaic (CPV) solar power generation systems with Fresnel lenses can significantly increase photoelectric conversion efficiency. Currently, solar power plants typically have an area of several square kilometers, which would require tens of billions of Fresnel lenses. Roll-to-roll (R2R) imprinting is a technique for continuously producing optical microstructures. The roller mold with Fresnel structure is critical to the R2R embossing process. However, the Fresnel structure of the roller mold is difficult to process, which puts high requirements on the existing machining technology and machine tool structure. The roller mold's quality and size also bring new challenges to mold surface inspection technology. Therefore, how to realize the machining and on-machine measurement of the Fresnel structure of the large-size roller mold has become a difficult problem for the mass production of Fresnel lenses.

This paper studies the manufacturing process of the Fresnel structure of the roller mold, including the design of the Fresnel lens and the simulation of the light-gathering performance, the cutting and machining method of the Fresnel structure of the roller mold, and the three-dimensional profile of the Fresnel structure of the roller mold. Measurement and on-machine measurement error separation methods. The main research work is as follows:

(1) Aiming at the difficult problem of radial Fresnel structure machining of large roller molds, a machining method for radial Fresnel structures of large roller molds, based on four-axis linkage of A-axis, C-axis, X-axis, and Z-axis, was developed. For the first time, the machining of radial Fresnel structure arrays has been realized on a roller machine tool. According to the design of the Fresnel lens, the selection of geometric parameters of the diamond tool, and the size of the roller, the machining path of the radial Fresnel structure of the roller mold is planned. The influence of the alignment error between the diamond tool tip and the machine tool's A-axis rotation center and the roller diameter measurement error on the Fresnel structure's processing is analyzed.

(2) Aiming at the problem of discontinuous machining track of high-filling Fresnel

structure array, a circular arc transition machining method is proposed, and the high-filling Fresnel structure array processing is realized on the roller machine tool for the first time. According to the two evaluation indexes of light-gathering performance and filling factor, optical simulation software optimizes the high-filling Fresnel lens. The machining of the trimmed region of the trimmed radial Fresnel structure array is prone to tool interference. The arc transition method is used to optimize the tool machining path of the trimmed region, and the tool radius compensation is performed. By simulating the three-dimensional shape of the Fresnel structure, the feed per revolution and the radius of the tool arc are determined, and the cutting experiment of the annular groove on the roller determines the cutting speed and cutting depth in the cutting parameters.

(3) To solve the problem of three-dimensional profile measurement of the microstructure of large roller molds, an on-machine measurement system based on position synchronous data acquisition technology was developed, and different measurement schemes were designed according to the microstructure characteristics of roller molds. The analysis of the motion error of the on-machine measurement system shows that the Z-axis horizontal straightness error has the most significant influence on the measurement results. A high-precision flat crystal is used to measure and compensate for the repeatability of the Z-axis horizontal straightness error. According to the characteristics of the radial Fresnel structure of the roller mold, the scanning measurement path is optimized by combining equal angles and arc lengths, improving the accuracy and efficiency of on-machine measurement.

(4) Aiming at the problem that the horizontal straightness of the Z-axis guide rail and the radial runout error of the spindle are challenging to compensate for large-scale roller machine tools, this paper researches its error separation technology. It proposes a two-point dislocation method based on a shearing platform, which separates The horizontal straightness error of the guide rail and the radial runout error of the spindle used to improve the accuracy of on-machine measurement. The algorithm of the straightness error and the radial runout error of the main shaft separated by the two-point dislocation method based on the shear platform is deduced. The influence of the Z-axis positioning error of the machine

tool, shearing platform positioning error, C-axis positioning error, and spectral probe noise on the reconstruction of the Fresnel structure section profile is analyzed through simulation. The analysis results show that the error effects are all at the sub-micron level.

(5) The roller mold Fresnel structure processing and on-machine measurement experiments were carried out. Radial and highly filled Fresnel structures are processed by the proposed processing method. The developed on-machine measurement system measured the three-dimensional profile of the Fresnel structure, and the measurement results were compared with the theoretical profile. The proposed two-point dislocation method measures the axial and radial cross-sectional profiles of the Fresnel structure of the roller mold, and the Z-axis horizontal straightness and C-axis radial runout errors are separated. Comparing the cross-sectional profile obtained by on-machine measurement with that measured by Taylor PGI 1240 profiler, the two results are in good agreement, which verifies the accuracy of the proposed on-machine measurement method.

Keywords: Roller mold; high filling Fresnel structure; ultra-precision machining; on-machine measurement; error separation