光学自由曲面的超精密加工技术及应用

Ultra－precision Machining Technique for Optecal Freeform and Its Application

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摘　要：光学自由曲面是指非对称性、不规则、不适合用统一的光学方程式来描述的光学曲面。自由曲面光学元件在光电产品及光通讯产品中的应用日益广泛。采用多轴超精密金刚石机床加工光学自由曲面，可达到亚微米级形状精度和纳米级表面粗糙的高精度水平。文章介绍了光学自由曲面的超精密加工技术及其在光电产品领域的应用，并开发适合几种典型光学自由曲面超精密加工的刀具轨迹自动生成软件。

关键词：超精密加工　光学自由曲面　刀具轨迹生成器

数码相机、传真机、扫描仪、激光雕刻机、光电显示器、光纤通讯等光电产品和光通讯产品已形成了一个数以万亿计的全球市场。自由曲面光学元件已成为用于光电及通讯产品的关键零部件。本文主要讨论V形槽列阵、微镜列阵和f－theta透镜等几种具有代表性的光学自由曲面。

V形槽光学曲面是指在基体介质上采用压痕、腐蚀、切削等方法加工出V形的沟槽，用于光纤或光电设备连接的光学元件。V形槽主要用于光纤接头、激光二极管、有源波导、无源波导、MEMS和光电开光等光电设备中。光纤阵列是下一代光通讯网络的关键设备之一。如图1所示是Senko Advanced Components, Inc.公司生产的光纤接头。该光纤接头的V形槽采用精密磨削的方法加工而成，能满足高精度、高均匀性的要求。如图2所示是OZ Optics公司生产的几种光纤接头。V形槽在各种背光组模部件中也得到了广泛应用。典型的背光组模主要由光源、光导通路等两部分组成。图3表示V形槽光导通路原理示意图。

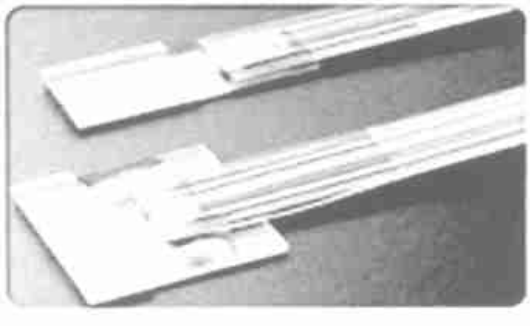
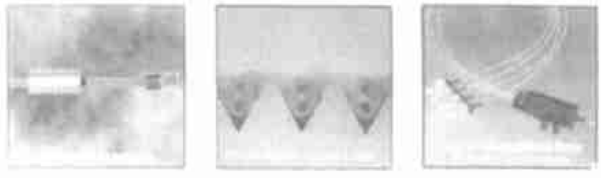


图1　Senko公司生产的光纤接头

微透镜阵列是指在一个平面基体上制作成一系列微透镜阵列，主要用于做显示设备的背光组模。如图4所示是用微透镜阵列做背光组模的LCD的结构示意图。



(a) 全密封V-Groove　(b) 光纤接头的端面　(c) V-Groove装配

图2　OZ Optics公司的光纤接头

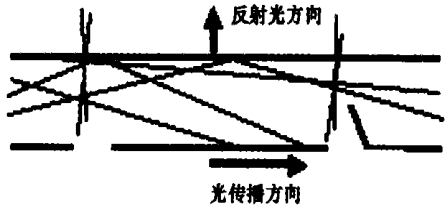


图3　V型槽光导通路原理示意图

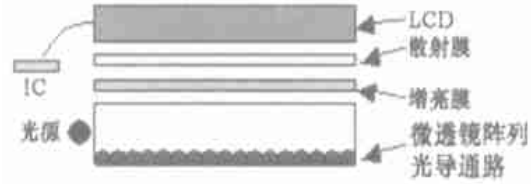


图4　微透镜阵列背光组模LCD的结构示意图

f－theta透镜主要用于扫描系统进行读取和打印。如图5所示，对于一般的光学透镜，当一束激光射向处于透镜焦点的反射镜时，光线通过反射镜反射和透镜折射后汇聚于透镜的像面上，其理想像高 $y = f \cdot \tan\theta$（其中：y 为像高，θ 为入射角，f 为透镜焦距），即像高 y 与入射角 θ 的正切值成正比。这种透镜用于激光扫描系统时，由于理想像高与扫描角 θ 之间不成线性关系，因此以等角速度偏转的入射光束在焦平面上的扫

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描速度并不是常数。为了实现等速扫描，应使聚焦透镜产生一定的负畸变，使它的实际像高比几何光学确定的理想像高小并与扫描角 θ 成线性关系，为此必须用两个或两个以上的镜片组成的镜片组来取代单个镜片。所谓 f—theta 镜，就是经过严格的设计，使像高与扫描角满足关系式 $y=f\cdot\theta$ 的镜头，因此 f—theta 镜又称线性镜头。如图 6 所示，是 3M Procision Lens 公司生产的用于激光打印机的 F—theta 镜。

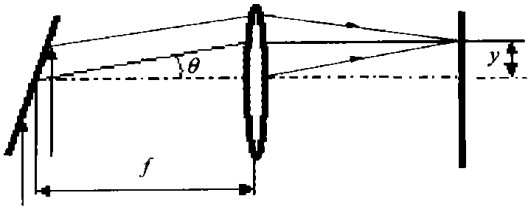

图5 一般光学透镜的成像原理示意图

图6 激光打印机用f-theta镜

1 光学自由曲面超精密加工技术

自由曲面光学元件的设计和制造与传统光学元件有很大的差别。传统的球面和非球面光学透镜有回转对称轴，用传统的 2 轴超精密车床就可以加工。传统的加工设备和加工技术很难满足高精度光电产品中复杂自由曲面的加工要求[1]。美国 Precitech Inc. 公司生产的超精密多轴自由曲面加工机床可以加工具有非对称轴的光学自由曲面，不需要抛光等后续加工就可以使加工精度达到亚微米级的形状精度和纳米级的表面粗糙度。

目前，多轴超精密加工技术方面的研究报道还比较少。有关自由曲面加工方面的研究工作大多针对普通多轴数控机床的端面铣削或球头铣削加工[2~9]。在多轴超精密机床上用单晶金刚石刀具加工 f—theta、微型沟槽和微透镜阵列等光学曲面的研究相对还是比较少。香港理工大学先进光学制造中心引入了一台大型超精密五轴自由曲面加工中心（Precitech Freeform 705G，如图 7）。适合于加工多种类型的光学元件及精密零件。其加工精度形状精度为亚微米级，表面粗糙度为纳米级。可进行三维自由曲面的铣削、磨削及飞刀加工，当然也可进行二维的超精密切削。加工设备除了拥有 3 个线性运动轴（x、y、z）外，还拥有 2 个旋转轴 B 轴和 C 轴。由于线性轴采用油静压导轨及配有反弹气垫，因而线性轴的移动具有极高的精度、重复精度、刚度及平稳度。其位置的反馈精度可达到 8.6 nm。主轴采用气浮轴承，其最高转速为 10 000 r/min。可加工最大工件直径为 700 mm。3 个方向的导轨行程分别为 350 mm（x）× 150 mm（y）× 250 mm（z）。

图7 超精密5轴自由曲面加工机床

图8 金刚石“飞刀”铣削加工

2 光学自由曲面刀具轨迹生成器

光学自由曲面在光学产品领域是一个崭新的概念，目前还没有统一算法对光学自由曲面进行设计和制造，数控编程比较困难。虽然有些光学设计软件（如 Focus Software 公司的 ZEMAX、Optical Research Associate 公司的 Code V）可以用来进行光学自由曲面的设计，但它们的输出格式都不适合数控编程。很多商用 CAD/CAM 软件（如 MasterCAM、Unigraphics 等）大都针对通用数控机床或加工中心，适合对端面铣削或球头加工的数控编程。通常采用单晶金刚石“飞刀”加工光学自由曲面（如图 8），不适合用普通的 CAM 软件进行自动数控编程。目前市场上还没有直接通过光学自由曲面的设计结果来获得数控加工程序的软件。光学自由曲面与普通自由曲面的数控加工相比有以下不同点：加工精度要求很高，刀具半径和形状误差的补偿量以及表面精度补偿都要达到微米或亚微米级的精度。为此我们研制了一套针对加工光学自由曲面的刀具轨迹生成器。

图 9 是光学自由曲面刀具轨迹生成器的基本功能模块示意图。光学自由曲面刀具轨迹生成器主要由信息数据管理、光学微结构设计、加工方法选择与切削参数优化、数控程序生成、数控程序检验与修改、数控加工仿真和输出等七大模块组成。信息数据管理模块主要用来对用户要求、产品特征、工件材料、刀具信息、加工参数等光学微结构刀具轨迹生成过程中所需要的所

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有信息进行分析和管理。光学微结构设计模块是指将光学设计结果转换成便于生成数控代码的表达方式。加工方法选择与切削参数优化模块主要是确定加工过程中加工路径(如 ZIG、ZIG-ZAG 方式),并对进刀、退刀、切削走刀、快速走刀、切削用量等有关加工参数进行选择和优化。数控程序生成模块根据光学微结构的设计结果和切削参数来自动生成加工光学微结构的数控程序。数控程序检验与修改模块对数控程序进行词法、语法等方面的检查,并可根据需要对自动生成的数控程序进行适当的修改。数控加工仿真模块是对数控程序进行刀具轨迹和三维动态仿真。输出模块对已经检验正确的数控程序、切削参数的优化结果以及仿真结果等内容按用户的要求输出。图 10、11、12 分别表示加工光纤通讯V-Groove 接口部件、微透镜阵列和f—theta 透镜的数控程序生成及仿真过程。

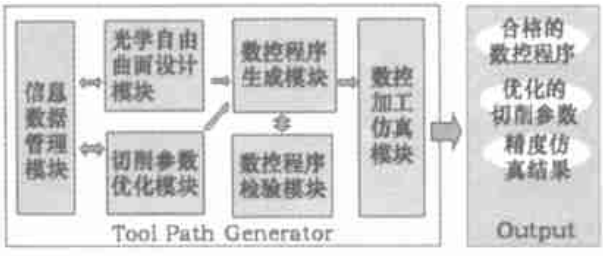

图9 光学自由曲面刀具轨迹生成器的基本功能模块

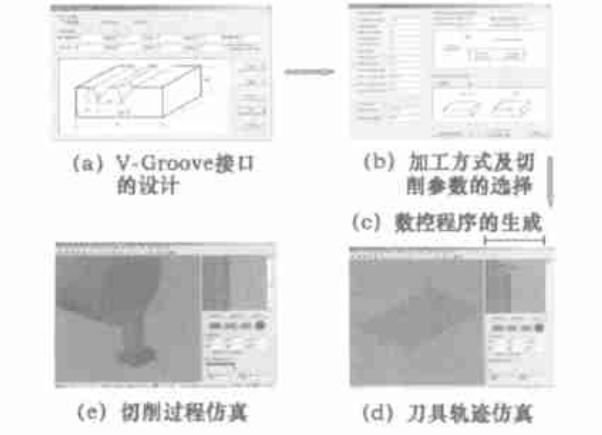

图10 光纤通讯V-Groove接口部件数控程序生成及仿真

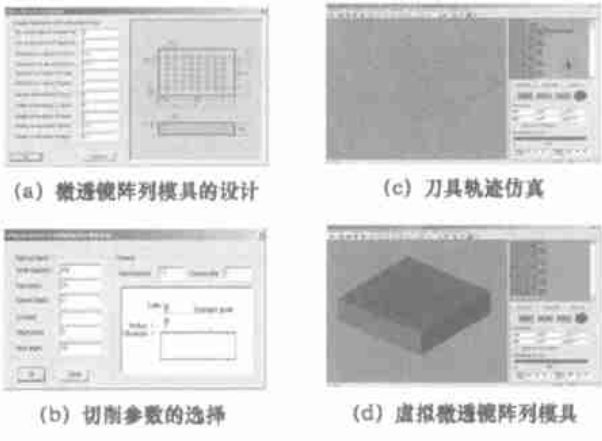

图11 微透镜阵列的数控加工程序生成和刀具轨迹仿真

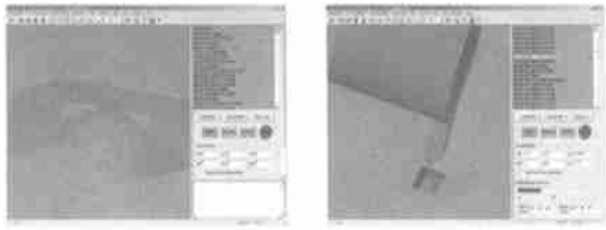

图12 f-theta透镜数控加工程序生成和切削仿真

3 结语

本文综述了自由曲面光学元件的市场趋势及加工技术,并介绍了由香港理工大学先进光学制造中心开发的一套光学自由曲面刀具轨迹生成软件,该软件可用于超精密 5 轴数控机床上加工光纤通讯元件、微透镜阵列和 f—theta 透镜等光学自由曲面。

参 考 文 献

1 Kurgano J., Suzuki H. and Kimura F. "Generation of NC Tool Path for Subdivision Surface," CAD/Graphics' 2002, 22—24 August, Kumming, International Academic Publisher, 2002: 1—7

2 Dragomatz D. and Mann S., A Classified Bibliography of Literature on NC Milling Path Generation, Computer-Aided Design, 1997, 29(3): 239—247

3 Balasubramaniam M., Ho S., Sarma S. and Adachi Y., Generation of Collision-free 5-axis Tool Path Using Haptic Surface, Computer-Aided Design, 2002, 34: 267—279

4 Kim T J. and Sarma S., Toolpath Generation along Directions of Maximum Kinematic Performance; a First Cut at Machine-optimal Paths, Computer-Aided Design, 2002, 34: 453—468

5 Tseng Y J. and Sue Y R., Machining of Free-form Solids Using an Octree Volume Decomposition Approach, International Journal of Production Research, 1999, 37(1): 49—72

6 Loney G C. and Ozsoy T M., Machining of Free Form Surfaces, Computer-Aided Design, 1987, 19(2): 85—90

7 Choi B K., and Jun C S., Ball-end Cutter Interference Avoidance in NC Machining of Sculptured Surfaces, Computer-Aiede Design, 1989, 21(6): 371—378

8 Elber G. and Cohen E., Toolpath Generation for Freeform Surface Models, Computer-Aiede Design, 1994, 26(6): 490—496

9 Huang Y. and Oliver J H., Non-constant Parameter NC Tool Path Generation on Sculptured Surfaces, International Journal of Advanced Manufacturing Technology, 1994(9): 281—290

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ABSTRACTS & KEYWORDS
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Ultra-precision Machining Technique for Optical Free-surface and Its Application

W. B. Lee (The Hong Kong Polytechnic University), et al. (17)

Abstract: Free-surface optical products are crucial to the development of complex and micro-optical-electro-mechanical devices used in many photonics products. The fabrication of high quality optical freeform lens is based on ultra-precision free-surface machining technology on multi-axes ultra-precision diamond machine, which allows direct machining of freeform surfaces with sub-micrometric form accuracy and nanometric surface finish. In this paper, the app. of ultra-precision free-surface machining to the fabrication of optical products is addressed. The methodologies for the development of the tool path generating software for three optical products are discussed.

Keywords: Ultra-precision Machining, Free-surface Optical Surface, Tool Path Generator

Research on Key Techniques of Inspection System for Aero-engine Turbine Blade Based on Industrial CT

CHENG Yunyong, et al. (North West University of Industry)(27)

Abstract: The industry computed Tomography inspection system could provide non-destruction, accurate, effective and complete inspection methods for aero-engine turbine blade production. The software of the inspection system organizes the blade CT slice images into a Three Dimensional Digital Sampling Model, on which performs inspecting and analyzing for blade dimension, profile deviation, wall thickness, casting defects etc, and at last generates the final inspection report. Some key techniques including blade Digital Sampling Model generating, profile deviation analyzing, and wall thickness inspecting were researched and validated by adopting a set of real turbine blade CT scanning data.

Key words: Industry Computed Tomography, Turbine Blade, Digital Sampling Model, Non-destruction Inspection

The Dependency and Promotion of Logistics Evolvement to Enterprise's Operating Mechanism
——A Practice of Synchronized Supply in Dongfeng Peugeot-Citroen Automobile Company

BO Jie (Citroen Wuhan Factory)(30)

Abstract: By analyzing the cases of synchronized supply in flexible manufacturing system in an automobile company, the article introduces a common issue in industrial engineering, the evolvement of logistics has both passive dependency and active promotion to the mechanism of an enterprise. At the same time, it emphasizes that the change of people's ideas is the prerequisite of the evolvement of logistics, and the evolvement is a thoroughly challenge to exist mechanism in enterprises. It is a system engineering that involves comprehensive cooperation of all departments in an enterprise.

Keywords: Evolvement of Logistics, JIT, Synchronized Supply, System Engineering

System Design of Multi-function Nut-fastening Machine Based on Closed Force

REN Yongqiang (Shanghai Jiaotong University), et al. (32)

Abstract: By analyzing the relationship between the axial pre-tightening force and the screw-in angle, torque, geometric parameter and friction factor of the connector, a multi-function nut-fastening machine based on closed force is designed, which is developed to work in rear axle and gearbox assembly line for several enterprises. The torque is displayed in real time by detecting torque sensor, both load and unload processes can be switched into fast or slow speed automatically by setting threshold torque, and have a good accuracy of torque control and efficiency within 800 N·m in whole process.

Keywords: Nut-fastening Machine, Closed Force, Axial Pre-tightening Force, Torque Control

Research on Structural Dynamic Optimal Design of NC Internal Grinder

HU Rufu (Southeast University), et al. (39)

Abstract: Structural dynamics optimal design of key components is the basis of optimal design of the whole machine tool. The method of sensitivity analysis is applied to optimize the arrangement shapes and parameters of the strengthened bars of components. The BP neural networks model of the spindle system is established and corrected through comparing it with the experimental result, thus the structure parameters of the spindle are optimized. These technologies will

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