CIRP Annals - Manufacturing Technology 64 (2015) 121–124

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Ultra-precision machining of radial Fresnel lens on roller moulds

Rui Huang [a,b], XinQuan Zhang [b,*], Mustafizur Rahman (1)[a], A. Senthil Kumar [a], Kui Liu [b]

[a] *National University of Singapore, 10 Kent Ridge Crescent, 119260 Singapore, Singapore*
[b] *Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, 638075 Singapore, Singapore*

ARTICLE INFO

Keywords:
Ultra-precision
Mould
Fresnel Lens

ABSTRACT

In Roll-to-Roll manufacturing of optical films, direct diamond turning of radial Fresnel lens structures on a roller mould was considered infeasible, due to the incapability to cut steep circular grooves on the outer cylindrical surface using conventional approach. This paper presents a novel solution to this problem. A four-axis interactive tool–workpiece motion is designed to precisely fabricate the complex microstructures. The tool path is generated from geometrical calculations considering the lens design, tool geometries and roller parameters. This process is experimentally verified with qualified profile quality and surface finish, thus making direct machining of radial Fresnel lens possible.

1. Introduction

A radial Fresnel lens is an optical component which has a wide variety of applications, e.g., advanced lighting systems and concentrated solar power systems, due to its light weight, small size and excellent optical performance. It is able to realize light collimation and concentration with much less lens materials compared to a conventional spherical lens by collapsing the continuous surface profile of the spherical lens onto a plane. Radial Fresnel lenses are usually fabricated by ultra-precision diamond machining [1], or by plastic injection moulding [2].

Roll-to-Roll (R2R) embossing provides an advanced solution for continuous manufacturing of various optical films such as brightness enhancement film, lenticular diffuser film, linear Fresnel lens film [3]. Through utilizing high-precision roller moulds patterned with micro/nano surface structures, R2R embossing is able to replicate such structures onto flexible film substrates with significantly higher throughput and lower cost compared to conventional injection moulding technology [4,5]. In general, the roller moulds applied in R2R embossing of optical films should be prepared by ultra-precision diamond machining, in order to achieve high profile accuracy and mirror-like surface finish of the machined feature.

Unfortunately, direct diamond turning of radial Fresnel lens structures on a roller mould was considered infeasible, due to its incapability to cut steep circular grooves on the outer cylindrical surface using conventional approach. In conventional diamond turning process, continuous rotational-symmetric structures can be easily generated on the roller periphery (e.g., linear Fresnel lenses [3]). With the assistance of Fast Tool Servo or Slow Slide Servo techniques, certain non-continuous and non-rotational-symmetric structures (e.g. gravure cells, micro lens array [6]) can also be machined on the roller with similar tool–workpiece setup in traditional diamond turning process. In some non-traditional diamond machining processes, *B*-axis was utilized to assist the adjustment of tool orientation, in order to realize machining of concave prismatic microstructures [7] and to improve shape precision of the spherical surface of Fresnel lens mould [8]. Being different from linear Fresnel lenses, a radial Fresnel lens is comprised of a series of central-symmetric steep circular grooves. Unfortunately, none of the above-mentioned techniques is capable of machining steep circular grooves on the roller, due to their fixed tool–workpiece relative position and limited degrees of freedom. Fig. 1 schematically describes the incapability of ultra-precision diamond turning approach in generating radial Fresnel lens structures on a roller. The dark shaded zone represents the portion where the work material cannot be removed due to the steep circular groove profiles and the fixed cutting angle.

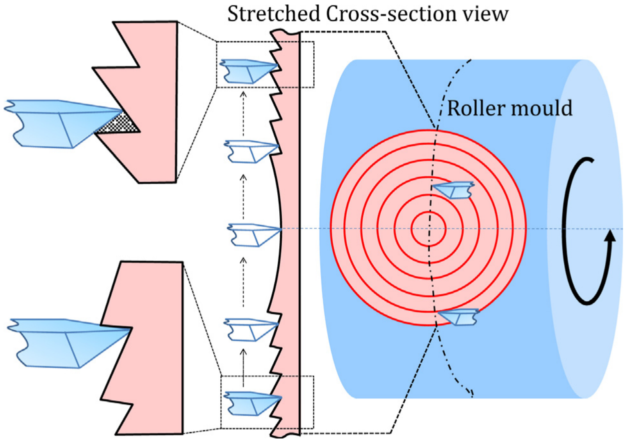

Fig. 1. Incapability to machine radial Fresnel lens on a roller using ultra-precision diamond turning method.

---

[*] Corresponding author.
E-mail address: zhangxq@SIMTech.a-star.edu.sg (X. Zhang).

http://dx.doi.org/10.1016/j.cirp.2015.04.062

As a result, the industry adopts an alternative method by replicating the radial Fresnel lens structures from a flat moulding plate onto a flexible electroplated metal sheet, which is then wrapped onto the outer cylindrical surface to form a structured roller mould. However, such plating and wrapping processes will introduce additional replication and assembly errors, and deteriorate the profile accuracy as well as the surface finish. This will eventually affect optical performance of the embossed Fresnel film and significantly limit its industry application.

Thus, in this study, a novel approach, Synchronized Tool and Roller (STR) diamond machining is developed to solve the problem illustrated above which is currently faced by the industry. A four-axis synchronized tool–workpiece interactive motion is designed to realize precise machining of the radial Fresnel lens microstructures containing steep circular grooves on the outer cylindrical surface. In this paper, tool path generation algorithm for this novel machining process is discussed in the following section, and experimental verification and analysis are presented thereafter.

2. Synchronized Tool and Roller (STR) diamond machining

In Section 1, the incapability of diamond turning of radial Fresnel lens on a roller was discussed. This challenge is overcome by the proposed STR diamond machining method and the process is illustrated in Section 2.1. In addition, the tool path was generated based on geometrical calculations considering the lens structure design, tool geometries and roller parameters.

2.1. Algorithm of lens structure generation on a roller

In order to solve the above-mentioned problem, an additional rotating motion of the tool is introduced to realize real-time adjustment of the tool orientation. A 5-axis ultra-precision machine system (including *X*-, *Y*-, *Z*-, *C*- and *B*-axes) with a customized tool–workpiece setting is utilized to realize the lens structure generation. B stage of the machine system is used as the rotating axis to hold the diamond tool, where the perpendicularity between the instantaneous tool–workpiece relative velocity and tool rake face can be constantly maintained. The motion of tool (*B*-axis rotation) and roller (reciprocating motion along *Z*-axis and swinging motion of *C*-axis) are to be synchronized via a 4-axis interactive movement. In the STR process, cutting is designed to take place only at the lowest position of the roller mould, as shown in Fig. 2.

In such case, STR diamond machining is able to imitate the ultra-precision diamond turning of the radial Fresnel lens on a flat surface, so as to enable direct machining of radial Fresnel lens structure on the roller periphery.

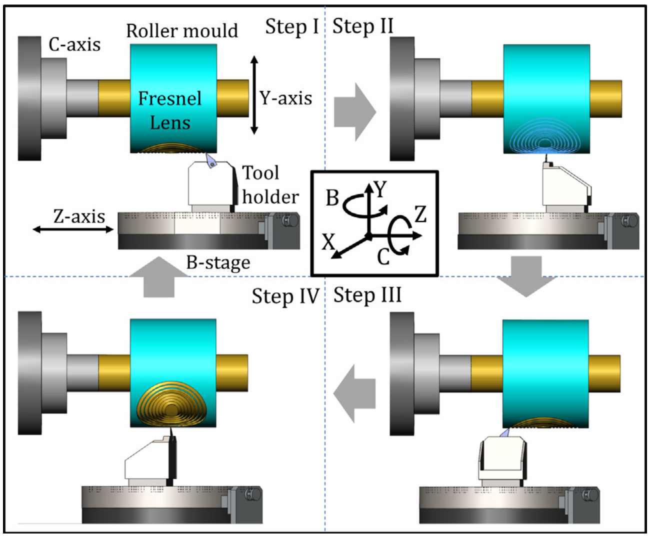

Fig. 2. Segmented motion simulation of STR diamond machining.

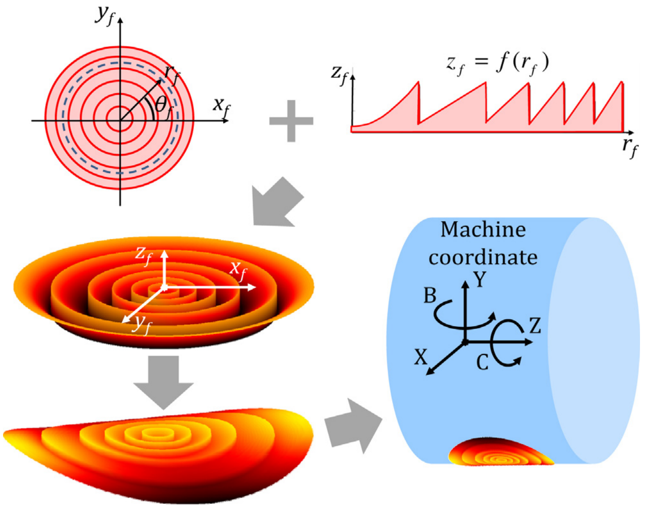

Fig. 3. Design phases of radial Fresnel lens structure on a roller.

To develop the tool path generation algorithm for the lens structure, the lens profile on the roller is firstly designed based on a given flat Fresnel lens, as shown in Fig. 3. A polar coordinate system (r_f, θ_f) is first used to describe the projection view of the flat radial Fresnel lens structure, with r_f being the radial coordinate and θ_f being the corresponding polar angle. To describe the 3D lens profile, the lens profile in the polar coordinate system is converted to a Cartesian coordinate system (x_f, y_f, z_f) as follows:

$$x_f = r_f \cdot \cos\theta_f \tag{1}$$

$$y_f = r_f \cdot \sin\theta_f \tag{2}$$

$$z_f = f(r_f) \tag{3}$$

where z_f is a function of r_f, and it represents the corresponding lens feature height for a point with a radial coordinate of r_f, as shown in Fig. 3.

The Fresnel lens structure on the roller surface usually has an equal height in order to avoid large-volume transverse flowing of the liquid resin and realize an even distribution of the resin during the embossing process. The lens profile, $f(r_f)$, is derived based on the given lens height, diameter, facet and draft angles.

In this study, as the lens structure generation is realized on the 5-axis machine system, it is necessary to convert the polar and Cartesian coordinates to the machine coordinates of the system (*X*, *Y*, *Z*, *C* and *B*). Fig. 4 illustrates the geometrical relationship of the tool–workpiece relative positions at two arbitrary points during the STR process. In the machining process, *C*- and *Z*-axes are programmed to perform a resultant rotary motion between the

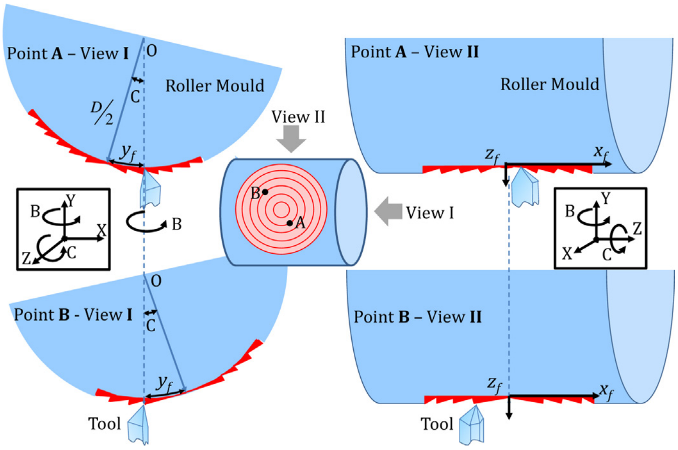

Fig. 4. Schematic illustration of tool–workpiece relative positions at two arbitrary points: A and B (View I: side cross-section view; View II: front cross-section view).