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Profile evaluation of radial Fresnel lens directly machined on roller molds by rotating-tool diamond turning

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ABSTRACT

In Roll-to-Roll manufacturing of high-quality optical Fresnel lens films, a high-precision roller mold with super-fine surface quality is essential to precisely transfer the functional microstructures from the periphery roller surface onto the flexible substrate. Unfortunately, direct diamond turning of deep circular grooves on the periphery surface of a roller mold was considered infeasible. Recently, the team has developed a novel 4-axis interactive tool-workpiece motion, Rotating-tool diamond turning (RDT), as a solution to overcome this challenge. Experiments were conducted to justify the capability of the proposed RDT process by directly machining a radial Fresnel lens on a brass roller mold, but without precise 3D profile evaluation of the lens on the roller surface. On-machine measurement of the machined lens structures using 3D touch probe is not applicable because the diameter of the probe is relatively large to penetrate into steep grooves of the Fresnel lens. On the other hand, off-machine measurement using stylus profilometer will introduce inevitable alignment errors during the measurement and lead to mismatched machining and measurement coordinates, making it difficult to evaluate the 3D lens profile generated by the RDT process eventually. In this study, a compensation and comparison algorithm is presented to precisely evaluate the form error between the machined and designed features in a three dimensional manner. Alignment errors generated when positioning the roller mold on the stylus profilometer are investigated and quantified through analyzing the characteristics of this unique micro structure with Fresnel lens wrapped on the roller periphery. As a conclusion, the machined lens structure is compensated and restored to compare with the designed profile, and the form error is obtained with the sources of errors analyzed. Such profile compensation and comparison method can be applied in other measurement and characterization studies on evaluation of complex optical structures patterned on roller molds for Roll-to-Roll manufacturing of advanced functional films.

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. Compared to conventional spherical lenses, it has the advantages of being lighter, thinner and easier to fit into compact optical systems, e.g. smartphone's camera system, due to its unique microstructures consisting of a series of concentric circular ring grooves. It is able to realize light collimation and concentration with much less lens materials 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 molding [2]. Other approaches to fabricate Fresnel lenses include precision grinding [3] and lithography [4].

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, etc. [5]. Through utilizing high-precision roller molds patterned with micro/nano surface structures, the emerging technique, R2R embossing, is able to replicate such structures onto flexible film substrates with significantly higher throughput and lower cost compared to conventional injection molding technology [6,7]. In general, the roller molds applied in R2R embossing of optical films are prepared by ultra-precision diamond machining, in order to achieve high profile accuracy and super-fine surface finish of the machined features. Unfortunately, direct diamond turning of radial Fresnel lens structures on a roller mold was thought to be

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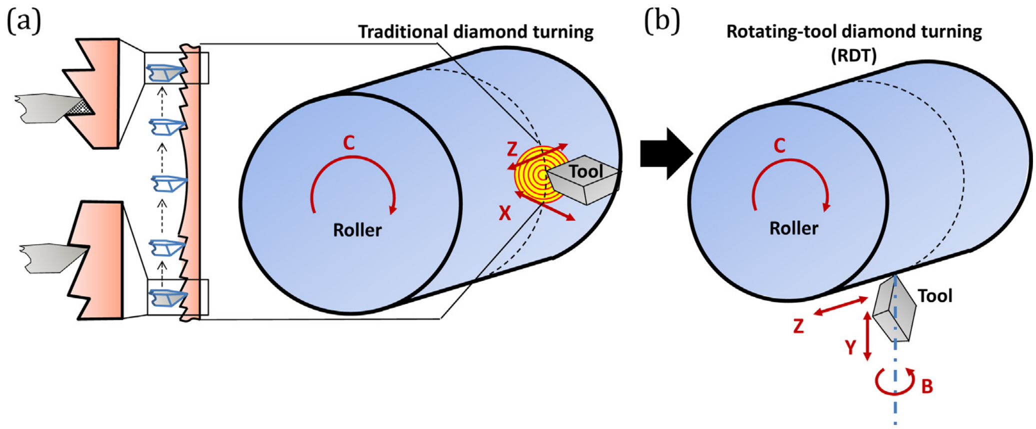

Fig. 1. (a) Incapability to machine radial Fresnel lens on a roller using traditional diamond turning method and (b) RDT method enables the continuous and synchronized variation of the tool orientation.

infeasible, due to its incapability to cut steep circular grooves on the outer cylindrical surface using conventional approach. In our previous study, a novel approach, Rotating-tool Diamond Turning (RDT) is developed to solve the problem illustrated above [8]. A 4-axis synchronized tool-workpiece motion is designed to realize precise machining of the radial Fresnel lens microstructures containing steep circular grooves on the outer cylindrical surface. A turning motion is imitated by this RDT process to cut the circular grooves on the outer cylindrical surface without causing any tool-workpiece interference during machining.

The capability of the RDT process has been experimentally verified by directly machining a radial Fresnel lens onto a brass roller periphery surface, but unfortunately with a lack of precise analytical evaluation of the machined feature. In general, on-machine measurement is preferred to evaluate such complex profile on a non-flat surface using a 3D touch probe attached to the machine [9,10], because the machining co-ordinates are kept and precisely aligned with the measurement co-ordinates. Zhang et al. [11] reported a combined on- and off-machine measurement to evaluate the free-form surface machined by diamond turning. Unfortunately, the on-machine measuring probe (diameter ≥ 1 mm) is relatively too large to penetrate into the deep micro grooves of Fresnel lens, which usually has a feature height less than 100 μm. As a result, off-machine measurement using a stylus profilometer solely is adopted in this study, which is usually used to examine the profile accuracy of conventional circular-symmetric optical lenses and molds. However, there is a lack of method to eliminate the large alignment errors between the roller mold and the stylus profilometer when measuring the machined complex optical features on the non-flat roller peripheral surface.

In this study, a compensation and comparison algorithm is developed to precisely evaluate the form error between the machined and designed features in a three dimensional manner. Alignment errors generated when positioning the roller mold on the stylus profilometer are investigated and quantified by analyzing the characteristics of this unique micro structure with Fresnel lens projected on roller. As a conclusion, the machined lens structure is compensated and restored to compare with the designed profile, and the form error is obtained with the sources of errors analyzed. Such profile compensation and comparison method can be applied in other measurement and characterization studies on evaluation of complex optical structures patterned on roller molds for Roll-to-Roll manufacturing of advanced functional films.

2. Rotating-tool diamond turning (RDT)

2.1. Method description

Continuous rotary-symmetric structures (e.g. linear Fresnel lenses [5]) can be generated on the periphery roller surface using traditional diamond turning method, while some non-rotary-symmetric microstructures (e.g. arrays of gravure cells [12]) can also be patterned on the roller by applying slow slide servo or fast tool servo with the same tool-workpiece setup as turning process. But such machining process using 3-axis tool-workpiece motion is not capable of generating radial Fresnel lenses on roller surface, because the diamond tool tip is not able to remove the deep corner zone of the steep circular grooves constituting the lens due to the fixed cutting angle (see Fig. 1(a)). To solve this issue, an additional rotating-tool motion is introduced to realize real-time adjustment of the tool orientation, and the B-axis is utilized as an additional rotatory axis to drive the synchronized rotating motion of the diamond tool (Fig. 1(b)).

In the RDT process, a 5-axis ultra-precision machine system with a novel tool-workpiece setup is adopted to enable the generation of radial Fresnel lens, as shown in Fig. 2. The detailed method description can be found in [8].

2.2. Off-machine measurement of the Fresnel lens profile machined by RDT

To verify the feasibility of the proposed RDT process, a given radial Fresnel lens was machined on a brass roller mold using a 5-axis ultra-precision machine system (Moore Nanotech 350FG). Technical details of the Fresnel lens and the roller mold can be found in Table 1. A stylus profilometer (Taylor-Hobson Form Talysurf) was used to measure the 3D profile of the machined radial Fresnel lens structure on the roller periphery (see Fig. 3(a)). In this setup, linear profile is measured from Z_0 to Z_1 (11 mm from Z_0 to Z_1 to cover the entire Fresnel lens of width 9.91 mm), at any arbitrary X position, the linear profile is represented by an array of feature height measurement Y, with the interval along Z axis defined before the measurement. In this study, the Z interval is set so that a total number of 4000 data points are gathered during one linear measurement from Z_0 to Z_1 (see Fig. 3(b)). After each linear measurement, the arm moves 10 μm along the X axis each time and is repeatedly performed. At the end of the measurement, a three-dimensional profile can be formed by combining a series of the linear profile into a 3D profile (see Fig. 3(c)). By comparing the