Precision Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

A theoretical and experimental investigation of orthogonal slow tool servo machining of wavy microstructured patterns on precision rollers

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ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 21 August 2015
Accepted 21 August 2015
Available online xxx

Keywords:
Precision roller
Microstructured patterns
Tool path generator
Orthogonal slow tool servo
Modelling and simulation
Ultra-precision machining

ABSTRACT

Precision cylinders, or rollers, with patterned microstructures on the surface are the key tooling component in the Roll-to-Roll and Roll-to-Plane fabrication process for precision manufacturing of microstructured plastic films. These films are widely used in optical applications such as the backlight guide and brightness enhancement films in LCD and LED displays. Compared with other fabrication processes, such as lithography, Single-Point Diamond Turning (SPDT), using a Fast Tool Servo (FTS) or Slow Tool Servo (STS) process, is an enabling and efficient machining method to fabricate microstructures. Most studies of the tool servo machining process focus on either machining microstructures in the axial direction for face machining of flat parts or in the radial direction on the surface of a precision roller. There is relatively little research work found on the machining of patterned microstructures on the surface of precision rollers using the tool servo in the axial direction. This paper presents a pilot study on the development of a tool path generator for machining wavy microstructure patterns on precision rollers by using an Orthogonal Slow Tool Servo (OSTS) process. The machining concept of OSTS is first explained, and then the tool path generator is developed in detail for machining wavy microstructure patterns on a roller surface. Modelling and simulation of pattern generation for different microstructures with different wavy patterns and grooves are presented based on the proposed tool path generator. Preliminary experimental work using SPDT on a 4-axis ultra-precision machine tool is presented and clearly shows the generation of unique wavy microstructure patterns on a precision roller. The machined wavy microstructures on the roller surface are measured and analyzed to evaluate the validity of the proposed tool path generator.

1. Introduction

Precision embossing by rolling, including roll-to-roll and roll-to-flat embossing, is an efficient machining process for manufacturing optical plastic films with microstructures, which are widely used in various applications such as the backlight guide in LCD/LED displays, optical thin films for holographic imaging applications, etc. [1]. The development of precision rolling technology has drawn great attention from industries and researchers. As the key tooling components in the rolling process, precision rollers with microstructures, especially of large dimensions (e.g. over 1000 mm) with microstructured features (e.g. a few μm), are very difficult to be machined with high precision and accuracy. There are different approaches found for generating precision rollers such as thin mould wrapping, laser ablation and machining, curved surface photolithography, etc. [2–4]. Tsai et al. [5] present a method for fabricating a seamless roller mould with wavy microstructures using a maskless curved surface beam pen lithography technique, which requires four steps including spray coating a thin photoresistant layer on the roller, exposing the layer though a translating micro-lens array, etching the patterned layer and electro-polishing the etched microstructures. A similar method was also studied by Chen et al. [6]. Yang et al. [7] proposed a method for fabricating a microstructured roller by mounting a flexible mould plate with microstructures to the periphery of a cylinder. Other common methods for fabricating a roller with microstructures are lithography and dry etching techniques [8].

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http://dx.doi.org/10.1016/j.precisioneng.2015.08.012
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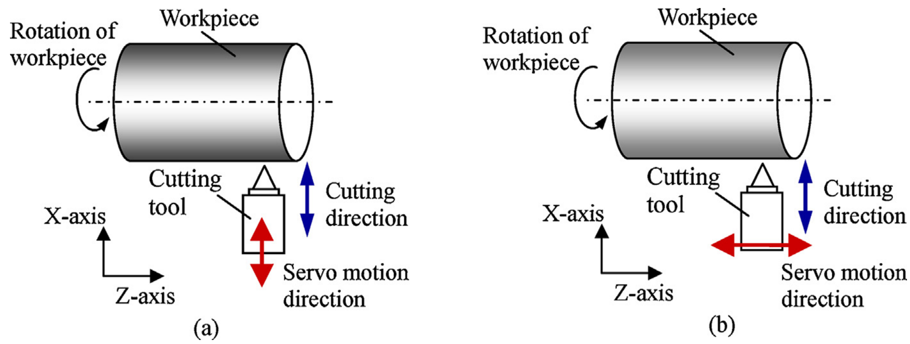

Fig. 1. Machining mechanism comparison between (a) traditional STS and (b) the proposed OSTS.

Compared with other machining processes such as lithography, Single-point Diamond Turning (SPDT) with a tool servo including Fast Tool Servo (FTS) and Slow Tool Servo (STS) is an enabling and efficient machining process to fabricate microstructures through a simple process to achieve optical surface finish directly, and the microstructured patterns can also be controlled precisely with various shapes. Furthermore, a microstructured pattern can be produced by the SPDT process in harder material such as nickel which will provide a much longer tool life in subsequent manufacturing processes. Most of the current studies on tool servo machining processes either focus on face machining of patterned microstructures, or on tool servo machining of microstructures in the radial direction of the precision roller [9]. There is relatively little research work found that studies the machining of patterned microstructures on precision rollers by using the tool servo in the axial direction. As a result, this paper presents a pilot study on the development of a tool path generator for machining wavy microstructured patterns on a precision roller by the Orthogonal Slow Tool Servo (OSTS) process. The machining mechanism of the proposed OSTS is firstly explained, based on which the tool path generator is developed for machining wavy microstructured patterns on a roller surface. Modelling and simulation of surface generation for different microstructures with different wavy patterns and grooves are explored based on the proposed tool path generator. Preliminary experimental work is conducted to study the generation of wavy microstructure patterns on a precision roller by using a 4-axis ultra-precision machine (Moore Nanotech 350FG). The machined wavy microstructures on the roller surface are then measured and analyzed to evaluate the validity of the proposed tool path generator. The present study provides a new machining process for manufacturing wavy microstructured patterns on a precision roller and hence extends the machining capacity of the existing machine tools.

2. Modelling of structured surface generation on a precision roller

2.1. Machining mechanism for an orthogonal slow tool servo

The Orthogonal Slow Tool Servo (OSTS) process is different from the traditional slow tool servo (STS) process. As shown in Fig. 1(a), the servo motion direction for a traditional STS is the same as the cutting direction, while the servo motion direction in OSTS is perpendicular to the cutting direction (see Fig. 1(b)). The difference makes the cutting mechanism and dynamics, tool path generation, tool wear, and so on of the OSTS different from those of traditional STS processes.

In the present study, a four-axis ultra-precision machining system is employed to machine wavy microstructured patterns on a cylindrical roller surface. As shown in Fig. 2 there are three

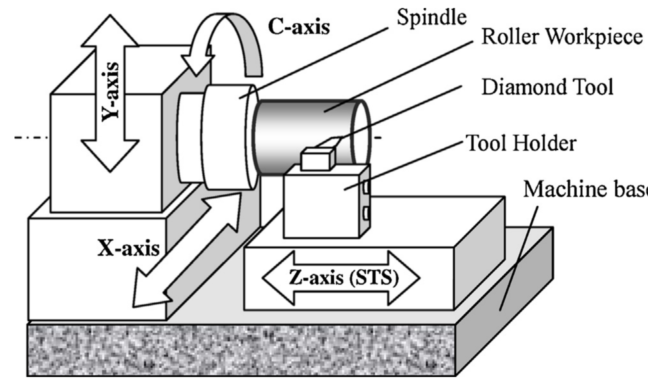

Fig. 2. Configuration of the machining system for the OSTS.

linear axes, i.e. X axis, Y axis, and Z axis, and a rotational axis, the C-axis. The roller workpiece is mounted on and rotated with the main spindle (C-axis), and the diamond cutting tool is mounted on the tool holder which is carried by the Z-axis. The slow slide servo is enabled during the machining process and hence the cutting tool moves along the Z-axis to implement the cutting process which is similar to traditional peripheral turning.

2.2. Tool path generation for SPDT with a STS

Fig. 3 shows a graphical illustration of the microstructured pattern generation on a roller surface using a STS. The machining parameters involved in the process include spindle speed (rpm) and feed rate (mm/min). Tool Path Generation (TPG) is used to calculate the tool tip position ($C_{sts}, X_{sts}, Z_{sts}$), that is, the position information of the three axes, i.e. C-axis (C_{sts}), X-axis (X_{sts}) and Z-axis (Z_{sts}). Based on Fig. 2, the TPG is obtained as follows:

$$\begin{cases} C_{sts} = \mathrm{mod}(\alpha, 2\pi) \\ X_{sts} = R_t \\ Z_{sts} = Z(t) \end{cases} \quad (1)$$

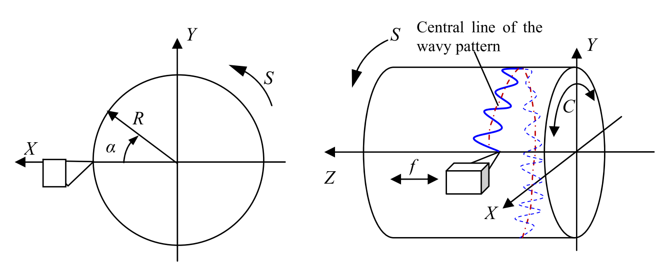

Fig. 3. Graphical illustration of microstructured pattern generation on a roller surface using a STS.