Design and Evaluation of Ultra Precision Roll Lathe for Large-scale Micro-structured Optical Films

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Abstract

In this paper, we demonstrate the design and performance evaluation of ultra precision horizontal roll lathe which is able to machine large cylindrical rolls up to ϕ600 x 2,500 mm (pattern length up to 2,000 mm). This machine consists of two linear axes (Z&X) and two rotary axes (C&B). In all axes including tail stock, hydrostatic oil bearings are adopted to implement high precision, stiffness and damping. Also, finite element analysis is performed to estimate and improve the machine performances such as structural deformation, vibration and thermal characteristics. Results of performance evaluation show that the designed roll lathe is capable of producing optical quality micro-patterns down to 30 μm on a large roll mold.

1 Introduction

Owing to increasing demands for large-scale micro-structured optical films in the field of flat panel display industry, much attention is being given to roll-to-roll forming process as an economical mass production method [1-2]. Ultra precision roll lathe is a high precision machine tool which is used to produce optical quality surface or complex micro-structures on a large roll mold by use of single point diamond cutting tools. Since it takes long time to generate micro patterns on a large roll surface, thermal stability during high speed operation is one of the most important requirements in the ultra precision roll lathe.

In this study, we present a design and analysis of ultra precision horizontal roll lathe which can machine large rolls up to ϕ600 x 2,500 mm (pattern length up to 2,000 mm). Results of performance evaluation on thermal characteristics and fine pitch machining are also demonstrated.

2 Design and Analysis of Ultra Precision Horizontal Roll Lathe

Fig. 1 shows structural layout of designed ultra precision roll lathe. The machine has a roll diameter capacity of 600 mm and a weight capacity of 600 kg. It consists of two linear driving axes (Z&X) and two rotary driving axes (C&B). The working strokes of Z and X axes are 2,320 mm and 260 mm, respectively.

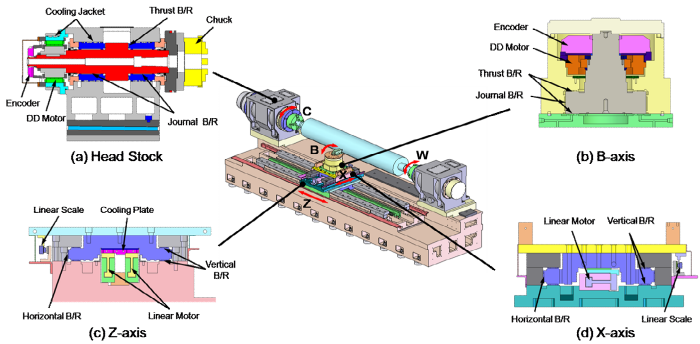


Figure 1: Layout of designed ultra precision horizontal roll lathe

In all axes, hydrostatic oil bearings are adopted to implement high precision, stiffness and damping. Low viscosity oil (2 cSt) is selected for work holding spindles(C&W) to reduce the heat generation from the bearings at the expense of flow rate. On the other hand, relatively high viscosity oil (10 cSt) is selected for the other axes of which the speed is low. Head stock spindle(C) and rotary tooling table (B) are driven by frameless direct drive motors, while coreless linear motors are used for two linear axes. Especially in Z-axis, double linear motor configuration is used against the heat generation during high speed repeated patterning process. High resolution glass encoders are used to feedback linear and rotary position, so the resolution can reach down to 1 nm in case of linear axes. As a controller, industrially proven UMAC system from Delta Tau Data Systems is adopted to ensure the robustness and flexibility in control. The design of tail stock is very similar to that of head stock, but the thrust bearing is removed to prevent over-constraint of roll by thermal expansion. Fig. 2(b) shows the result of FEM for total structural deformation and Fig. 2(c) shows the deformation in X-direction. Even though the deformation of the roll in Y-direction is about 73 μm, its effect on machining accuracy is quite small because cutting action happens on the side of the roll. The deformation of the roll in X-direction is about 6.5 μm, but it is very uniform over the full length of the roll. The deformation at tool position according to the Z-axis position is given in Fig. 2(d). These results mean that the effect of structural deformations on the machining accuracy can be maintained less than 1 μm.

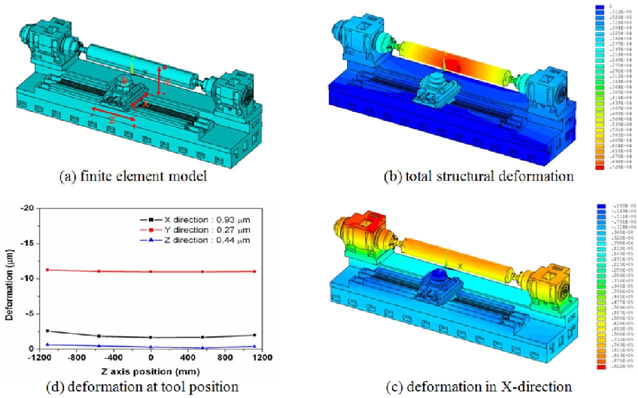
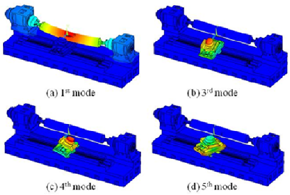


Figure 2: Results of structural analysis

Except the roll vibration (Mass of the roll can be changed.), main vibration modes come from Z-axis table (roll, pitch and yaw motion) and are affected by the stiffness of the hydrostatic oil bearings. The frequencies of those modes range 73.9 Hz ~ 85.2 Hz. Since the main excitation frequency ranges from 5 to 10 Hz considering the rotation speed of work holding spindles (normally 300~600 rpm), results of modal analysis may infer that the stiffness of the roll lathe is high enough. Fig. 4 shows the results of thermal analysis for temperature rise. For the calculation of heat generated from the hydrostatic oil bearings, speeds are assumed to be 300 rpm for C&W axes and 20 m/min for Z&X axes. Heat generation from spindle motor is set to 10 W by experience. The cooling capacity of the cooler is 2.9 kW. It is assumed that same amount of cooling capacity is distributed to spindle motor, head stock and tail stock. Maximum temperature rise is about 1.17 °C at the thrust bearing of head stock. Temperature rise of the tail stock is relatively small compared with that of head stock. The temperature rise of the roll is negligible, which mean that the roll is free from thermal expansion.



	Frequency	Remark
1st mode	67.8 Hz	Roll : horizontal direction
2nd mode	71.0 Hz	Roll : vertical direction
3rd mode	73.9 Hz	Z : roll direction
4th mode	75.1 Hz	Z : pitch direction
5th mode	85.2 Hz	Z : Yaw direction

Figure 3: Modal analysis

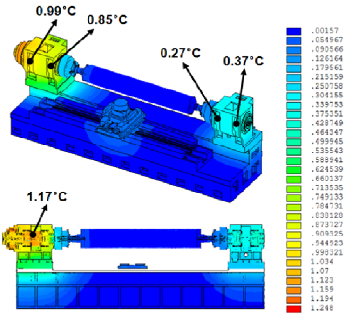
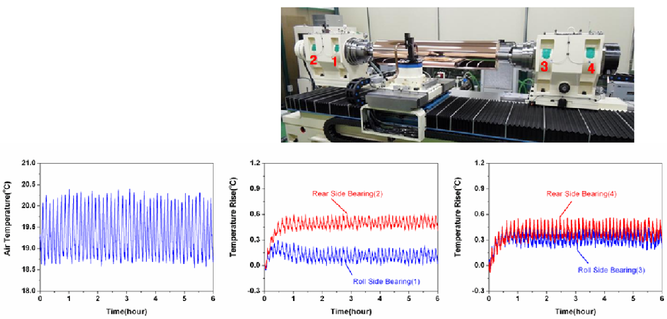


Figure 4: Thermal analysis

3 Performance Evaluation

Fig. 5 shows the picture of assembled prototype and temperature rise characteristics. During 300 rpm rotation, maximum temperature rise of the spindle at the outer surface is about 0.5 °C. Compared with FEM results in Fig. 4, the temperature rise of the head stock is a little bit lower than that of estimation, but they do not show big difference. This phenomenon can explained from the difference of real bearing clearance between head stock and tail stock since the heat generation at the hydrostatic bearing is greatly affected by bearing clearance. Temperature of the spindle is stabilized within 1 hour thanks to the cooling of spindle motor and hydrostatic bearings.



(a) Air temperature (b) Temperature rise of head stock (c) Temperature rise of tail stock

Figure 5: Thermal test (300 rpm)

Fig. 6 shows the SEM picture of machined prism patterns. As seen in the picture, optical quality prism pattens with 30 μm pitch are successfully machined regardless of the roll positions.

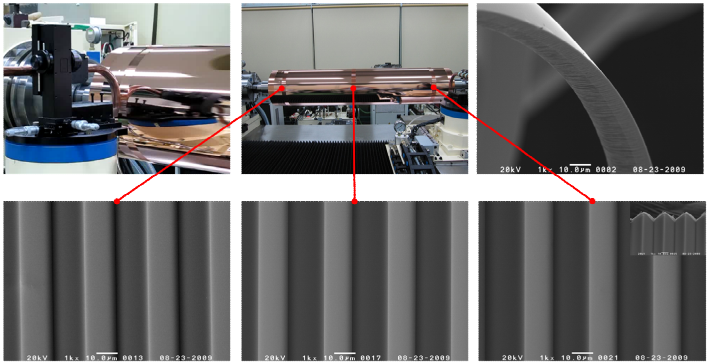


Figure 6: Results of fine pitch machining (30 µm pitch)

4 Conclusion

In this research, an ultra precision horizontal roll lathe, which is able to machine large cylindrical rolls up to ϕ600 x 2500 mm, has been designed, analyzed and evaluated. To achieve high precision and stiffness, hydrostatic oil bearings were adopted in all axes. Also, we realized non-contact driving by use of coreless linear motors and direct drive rotary motors. Results of structural analysis showed that the effect of structural deformations on the machining accuracy can be maintained less than 1 µm. Maximum temperature rise at the spindle outer surface was about 0.5°C and stabilized within 1 hour. Results of performance evaluation show that the designed roll lathe is capable of producing optical quality micro-patterns down to 30 µm on a large roll mold.

References:

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