

## Improvement of machining quality of copper-plated roll mold by controlling temperature variation

Tae-Jin JE<sup>1</sup>, Eun-Chae JEON<sup>1</sup>, Sang-Cheon PARK<sup>1</sup>, Doo-Sun CHOI<sup>1</sup>,  
Kyung-Hyun WHANG<sup>1</sup>, Myung-Chang KANG<sup>2</sup>

1. Division of Nano-Mechanical Systems, Korea Institute of Machinery and Materials, Daejeon 305-343, Korea;  
2. National Core Research Center for Hybrid Materials Solution, Pusan National University, Busan 609-735, Korea

Received 21 April 2010; accepted 10 September 2010

**Abstract:** Micro prism film used in LCD industry can be manufactured by roll to roll method with copper-plated roll mold. As copper-plated roll mold is getting larger, pitch error is getting severer. The pitch error drops the quality of micro prism film. The main cause of the pitch error was investigated during machining large roll mold whose machined length was 1 200 mm. The temperature of machining system was elevated during machining roll mold, and this elevation induced thermal expansion of the system. The temperature variation around the roll mold also made thermal expansion of the roll mold. The amount of thermal expansion had strong relationship to the amount of pitch error. Therefore, the roll mold was machined after warming-up of machining system and precise temperature controller around copper-plated roll mold was installed, which minimized the temperature variation. Finally, precise micro prism patterns without pitch error were machined on the large roll mold.

**Key words:** copper-plated roll mold; machining; prism pattern; temperature variation

### 1 Introduction

Micro prism film is used at liquid crystal display (LCD) back light units (BLU) for enhancing luminance and light efficacy[1]. There were a few studies[2–5] about the shape of optical pattern for enhancing luminance; however, there was seldom research about manufacturing method. Micro prism film is manufactured by roll to roll method using machined roll mold. As display is getting larger, it is more important to machine ultra-fine patterns on longer copper-plated roll mold[6–7]. It is needed to analyze several parameters such as machining system, tool, mold material, machining conditions, and circumstance for meeting the demand[8–10]. Especially, the temperature variation of machining system and roll mold can change the pattern accuracy severely when machining several tens of micrometer patterns on roll mold. The effect of temperature variation of roll machining system and copper-plated roll mold on machining quality was analyzed, and the quality was improved in this study.

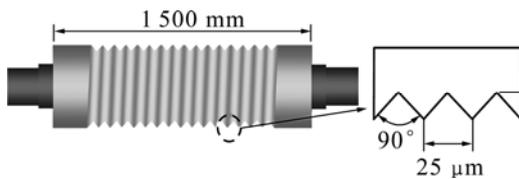
### 2 Experimental

The ultra precision machining system used in this study was reported in previous works[6]. The main specifications are displayed in Table 1. The machining system has an ultra-fine lathe with hydrostatic spindles which can rotate roll mold up to 350 kg at 500 r/min. The stage is controlled by linear motor and has accuracy of 0.01  $\mu\text{m}$  for X and Z axes. The maximum movements of Z axis (roll length direction) are 200 mm and 1 600 mm, respectively. The machining system can handle large mold up to 2 000 mm length. C-axis spindle can divide circumference into 0.000 1°.

Micro prism pattern was machined on copper-plated roll mold to verify how much the variation of temperature generates error on machined shape of pattern. Figure 1 shows the shape of the micro prism pattern. The diameter of the roll mold was 320 mm and the whole length was 1 500 mm. The actual machined length was 1 200 mm, which was coated by 700  $\mu\text{m}$  thick Cu. The pitch, depth and shape angle were 25  $\mu\text{m}$ , 12.5  $\mu\text{m}$  and

**Table 1** Specification of machining system

Item	Specification
Spindle bearing	Hydrostatic bearing
Spindle velocity/(r·min <sup>-1</sup> )	10–500
Movement length of Z-axis/mm	1 600
X, Z-axis minimum unit/μm	0.01
X, Z-axis cutting feed-rate/(mm·min <sup>-1</sup> )	0.01–3 000
Maximum work piece mass/kg	350

**Fig.1** Machining method of prism pattern

90°, respectively.

The prism pattern was cut by single crystal natural diamond cutting tool having shape angle of 90°. The roll mold was rotated at 300 r/min, the tool was moved to center of roll mold until reaching the cutting depth, and then was moved to length direction for machining the spiral micro prism pattern, as shown in Fig.1. The cutting process consisted of three stages, 7 μm, 5 μm and 3 μm, therefore, the total cutting depth was 15 μm.

Figure 2 shows a schematic diagram of the experimental system for analyzing the effects of temperature variation and displacement variation of spindles and copper-plated roll mold. The system consisted of fixed main spindle and sub spindle adjustable to roll mold length. Thermal couples were

attached on the main spindle and the free sub spindle, and can measure temperature variation of 0.001 °C, as shown in Fig.3. The measured variation was recorded by DAQ (data acquisition) and PC. Laser displacement sensor was also set to measure axial displacement (0.1 μm resolution) induced by the temperature variation of the spindles and the data were recoded at data acquisition module, as presented in Fig.4. Thermal expansion of roll mold itself was also measured. Temperature around the roll mold was elevated from 23.0 °C to 24.0 °C. Displacement and temperature of each end of the roll mold were recorded during temperature elevation.

### 3 Results and discussion

Figure 5 shows a simple diagram of copper-plated roll mold and the locations of observation after machining. Since the left of the roll mold was fixed by the main spindle and the right was attached to the sub spindle which was a free end, the five points were selected along the roll mold length direction. Point *E* was a starting point of machining, and points *D*, *C*, *B* and *A* were away from point *E* by 300, 600, 900 and 1 200 mm, respectively. The machined shape of the micro prism pattern was observed and analyzed at each point.

Photos of silicon replicas from the machined roll surface taken by SEM and microscope are presented in Fig.6. The prism patterns at points *A* and *B* were machined accurately. Small dual thread between two patterns was observed at point *C*. The dual thread was getting more severe at points *D* and *E*. The pitches of the dual thread at points *C*, *D* and *E* were 2.54 μm, 3.52 μm and 5.86 μm, respectively. The ideal case is no dual thread or dual thread smaller than 1 μm.

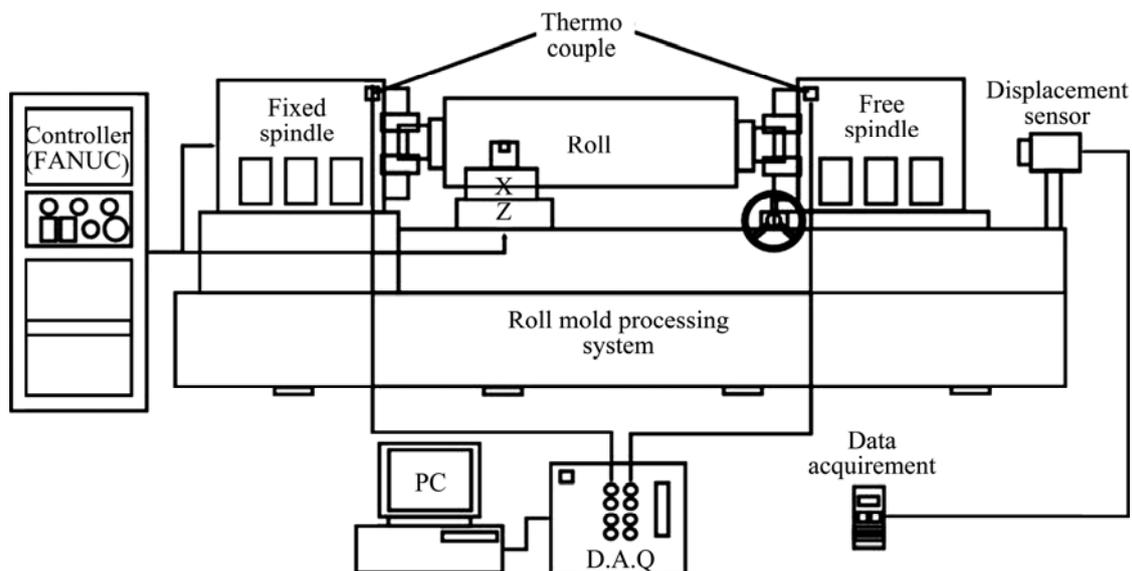
**Fig.2** Schematic diagram of experimental system



Fig.3 Thermal couples on main spindle and sub spindle



Fig.4 Laser displacement sensor and data acquisition module

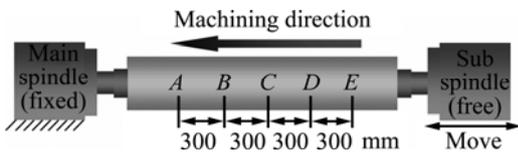


Fig.5 Simple diagram of points of pattern shape observation

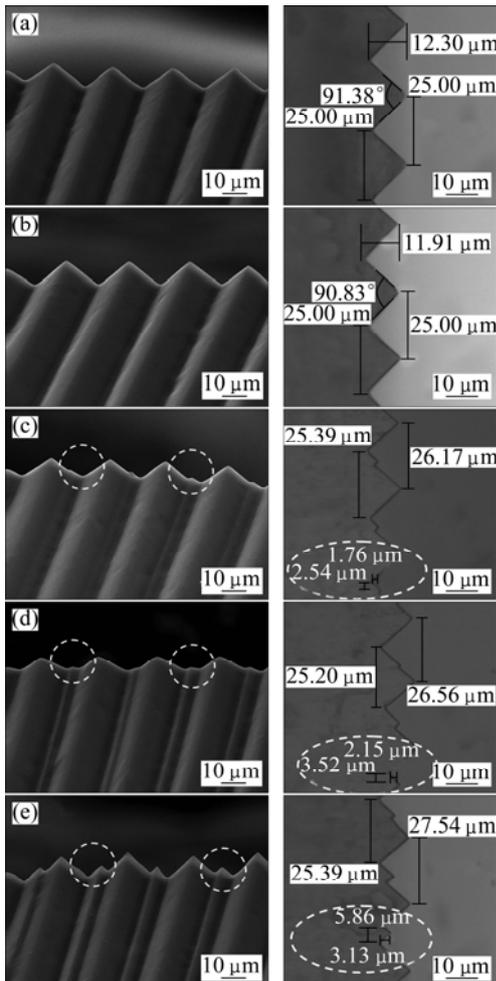


Fig.6 Features of machined patterns on roll mold surface: (a) Point A; (b) Point B; (c) Point C; (d) Point D; (e) Point E

Figure 7 shows the displacement of the spindles in every 5 min. Temperature of the spindles was elevated from 21.8 °C to 24.4 °C in about 1 h. Then, the temperature was elevated much slowly and finally was stable after about 2 h. The displacement of the spindles was about 5 μm during the temperature elevation. The temperature elevation of 1 °C might induce about 1.7 μm of displacement.

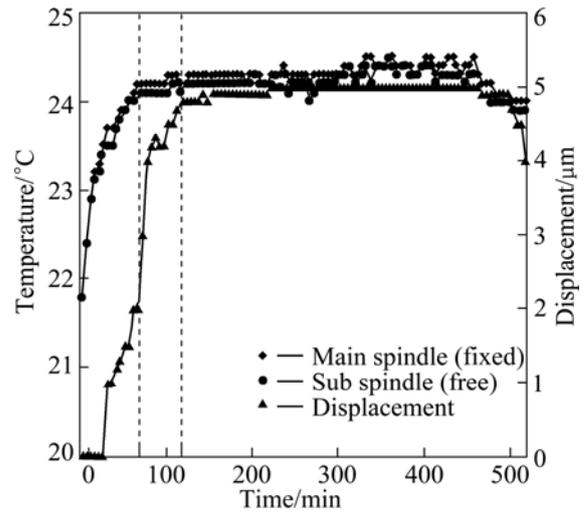
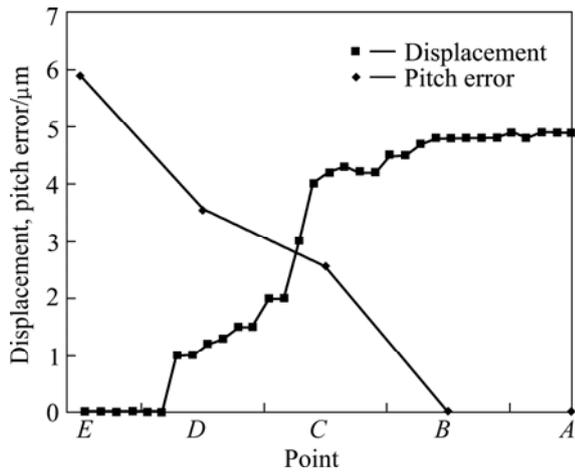


Fig.7 Variation of displacement (length direction) and temperature at spindles

Figure 8 shows the relationship between the quantitative pitch errors and the measured displacement variation of the main spindle at the first prism pattern machining. As shown in Fig.8, there was no displacement variation when point E was machined, and the displacement variation was almost saturated when points B and A were machined. Point E was machined before thermal expansion of the main spindle, points D and C were machined during thermal expansion, and points B and A were machined after thermal expansion. Since thermal expansion was saturated after the first prism pattern machining, all points were machined after thermal expansion at the second and the third prism pattern machining. Therefore, locations of the second machining at points E, D and C were different from the locations of the first machining. This explanation can be verified by Table 3. Quantitative pitch errors of each point were similar to displacement difference between the first machining and the second machining. Therefore, the thermal expansion of the spindles was important factor to make the pitch error. And, the effects of the thermal expansion of the spindles can be eliminated by starting pattern machining after 2 h warming-up of the machining system.

The surface temperature of the copper-plated roll

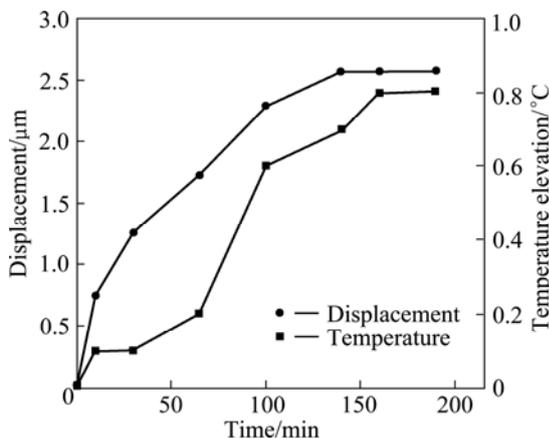
mold also affects the machining quality. When the environmental temperature around the roll mold was elevated from 23.0 °C to 24.0 °C in 1 h, the surface temperature was elevated by 0.8 °C, as shown in Fig.9. The surface temperature reached stable state after about 3 h. The length of the roll mold increased by 2.5 μm simultaneously. Therefore, temperature variation should be controlled under 0.4 °C in order to make the length



**Fig.8** Comparison between quantitative pitch errors and measured displacement variation of main spindle

**Table 3** Comparison between quantitative pitch errors and displacement difference

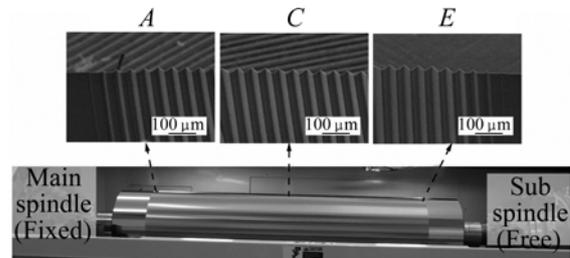
Point	Pitch error/μm	Displacement difference (1st and 2nd machining)/μm
E	5.86	5.0
D	3.52	3.8
C	2.54	0.8
B	0	0.1
A	0	0.1



**Fig.9** Variation of displacement (length direction) and temperature at spindles

change of the copper-plated roll mold under 1 μm. Separate precise temperature controller ( $\pm 0.2$  °C) was installed to sort out the problem. The machining system has a door shown in Fig.1, which enables us to control the temperature variation around the copper-plated roll mold easier.

Based on the results above, prism pattern was re-machined with the precise temperature controller after 2 h warming-up of the machining system. There was no dual thread and no pitch error on whole roll mold surface from point A (near main spindle) to point E (near sub spindle), as shown in Fig.10. Therefore, it was verified that precise temperature control at environment around roll mold should be performed with warming-up of spindles for machining perfect micro prism pattern on copper-plated roll mold.



**Fig.10** Final machining result of micro prism pattern on copper-plated roll mold

### 4 Conclusions

- 1) The main factors making pitch error at micro prism pattern on roll mold are temperature elevation at spindles and temperature change around copper-plated roll mold.
- 2) Warming-up of machining system in about 2 h is needed for stabilizing temperature at spindles when machining precise micro prism pattern.
- 3) Precise temperature control around copper-plated roll mold should be done for avoiding pitch error on copper-plated roll mold due to volume change of copper-plated roll mold.
- 4) Precise micro prism pattern was machined very accurately on large copper-plated roll mold (diameter 320 mm, length 1 600 mm, machined area 1 200 mm) after temperature control.

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(Edited by YUAN Sai-qian)