Precision Measurement of Vertical Straightness of a Roll Workpiece on an Ultra-Precision Lathe

Tohoku University ○Zengyuan NIU, Daiki MATSUURA, Yuanliu CHEN, Yuki SHIMIZU, So ITO, Wei GAO

Abstract:
This paper presents a measurement method for vertical straightness of a roll workpiece on an ultra-precision lathe. The measurement of the vertical straightness of a roll workpiece is directly influenced by the vertical error motions of carriage slide, which is composed of the out-of-straightness error component and the out-of-parallelism error component. In addition, the form error of cylinder also influences the measurement accuracy of the deflection of a roll workpiece. In order to carry out an accurate measurement of the vertical straightness of a roll workpiece, the influence due to the vertical error motions and form error should be compensated in the measurement of vertical straightness of a roll workpiece. A three-probe method and new algorithm have been employed for the measurement and evaluation of both the vertical straightness, which has two probes to the each other with roll workpiece between them in horizontal plane and one probe is arranged above roll workpiece in vertical plane. In this method, the form error can be removed by the conventional reversal method. The error motions of carriage slide are also measured by the three-probe method to compensate the measurement of the deflection. To verify the proposed algorithm, the experiments were conducted on a small roll workpiece.

1. Introduction

Ultra-precision drum roll dies are important industrial tools for fabrication of micro-structured roll dies for roll-to-roll processing of micro-structured optical films in industries such as flexible displays and solar cell. Because the diamond cutting tool has an extremely effective performance, the machining accuracy of a roll workpiece is basically determined by the motion accuracies of the spindle and the carriage slide. With the advancement in the applications of the precision roll dies, the next-generation drum roll lathe is required to fabricate roll dies with a capacity of up to be 2000 mm (length) and 500 mm (diameter) with a form fabrication tolerance less than 2 μm [1]. The weight of such a roll die can reach to be 3000 kg. It is therefore very challenging to fabricate such a large-scale roll dies with micrometric accuracy due to the deflection of roll die in vertical plane (vertical straightness) by gravity. For well satisfying the demand of large-scale roll dies with micrometric accuracy, the vertical straightness of roll dies should be inspected and fed back to the fabrication process [2-3].

However, the measurement of vertical straightness is limited by the error motions of carriage slide in vertical plane (vertical error motions). In additional, vertical straightness is generated by gravity and always forms a downward curve. Therefore, vertical straightness cannot be evaluated by using the conventional methods because the error motions in vertical plane cannot be eliminated.

This paper presents a new method for measurement of vertical straightness of a roll workpiece. In this method, two of three probes were arranged to the faced to each other with the roll workpiece between them in horizontal plane and one was arranged in vertical plane above the roll workpiece. The vertical error motions are also measured and evaluated by the three-probe method with new algorithms. And then, the measured vertical error motions are used to compensate the measured valuates of the vertical straightness. The preliminary experiments were carried out on a small roll workpiece.

2. Measurement principle

The measurement method of vertical straightness is shown in Fig. 1. Before rotation, the probe A, B and C scan the roll workpiece along the dashed lines from the start position $z_i$ to the end position $z_e$ while the workpiece is kept stationary. The output of probes can be expressed as follows,

$$m_i(z, \theta) = f(z, \theta) + \beta \cdot z + e_A(z) + \alpha \cdot z $$

(1)

$$m_o(z, \theta) = f(z, \theta + \pi) + \beta \cdot z - e_A(z) - \alpha \cdot z $$

(2)

$$m_c(z, \theta) = f(z, \theta + \frac{\pi}{2}) + \beta \cdot z - e_A(z) - e_B(z) + w(z) $$

(3)

where $f(z, \theta)$ and $\beta \cdot z$ are the nonlinear form error and the linear form error of roll workpiece. $e_A(z)$ and $-\alpha \cdot z$ are the horizontal out-of-straightness error and the horizontal out-of-parallelism error. $e_B(z)$ and $e_B(z)$ are the vertical out-of-straightness error and the vertical out-of-parallelism error. $w(z)$ is the vertical straightness of the roll workpiece. Then, the roll workpiece is rotated $90^\circ$ for the probe A, B and C to scan the roll workpiece again along the dashed lines. The output of probes can be written as:

$$m_i(z, \theta + \frac{\pi}{2}) = f(z, \theta + \frac{\pi}{2}) + \beta \cdot z + e_A(z) + \alpha \cdot z $$

(4)

$$m_o(z, \theta + \frac{\pi}{2}) = f(z, \theta + \frac{\pi}{2} + \pi) + \beta \cdot z - e_A(z) - \alpha \cdot z $$

(5)

$$m_c(z, \theta + \frac{\pi}{2}) = f(z, \theta + \frac{\pi}{2} + \pi) + \beta \cdot z - e_A(z) - e_B(z) + w(z) $$

(6)

It can be seen that the measurement of vertical straightness $w(z)$ is influenced by the form errors of roll workpiece, and the error motions. $w(z)$ can be expressed as:

$$w(z) = \frac{1}{2} \left[ m_i(z, \theta) + m_c(z, \theta) \right] - \left[ e_A(z) + e_B(z) \right]$$

(7)

The form errors can be expressed as:

$$m_i(z, \theta + \frac{\pi}{2}) + m_c(z, \theta) = f(z, \theta + \pi) + f(z, \theta + \pi) + 2\beta \cdot z $$

(8)

The vertical straightness can be re-expressed as follow:

$$w(z) = \frac{1}{2} \left[ m_i(z, \theta) + m_c(z, \theta) - m_i(z, \theta + \frac{\pi}{2}) + m_c(z, \theta + \frac{\pi}{2}) \right] - \left[ e_A(z) + e_B(z) \right]$$

(9)

It can be seen that this method is effective for measurement of vertical straightness. In order to compensating the vertical error motion in Eq. (9), the vertical error motions should be measured to compensate the vertical error motion to achieve an accurate vertical straightness.
The vertical out-of-straighness error $e_{\perp}(z)$ is measured on a straightedge by using the reversal method and the three-probe method with the same measurement structure in Fig. 1 and evaluated by Eq. (10). The vertical out-of-parallelism error $\varepsilon_{z}$ is measured on a small roll workpiece by using the error separation method and the three-probe method and evaluated by Eq. (11).

$$e_{\perp}(z) = \frac{1}{2}(m_{B}(z) + m_{C}(z))$$

$$\varepsilon_{z} = \Delta m_{W}(z) \frac{1}{2}(m_{B}(z, \theta) + m_{C}(z, \theta)) - 2m_{A}(z, \theta)$$

### 3. Experiments

Experiments were carried out on an ultra-precision lathe turning machine with a T-base design. The roll workpiece has a diameter of 55 mm and a length of 150 mm, mounted on the spindle. The roll workpiece was rotated with the spindle speed of 500 rpm and a Z-slide movement speed of 10 mm/min. The surface of the roll workpiece was cut by a diamond turning tool (self-cutting) over a length of 140 mm to make mirror surface for reducing the irregular surface error. Three capacitive displacement sensors were employed.

In the measurement result of the vertical out-of-straightness motion error $e_{\perp}(z)$ of the Z-slide, the probes were moved by the Z-slide with a speed of 150 mm/min, the sampling interval was 5 $\mu$m and the effective measurement length of the roll workpiece was 100 mm. The measurement was repeated ten times. The averaged measurement value of the vertical out-of-straightness error over ten times was approximately 146 $\mu$m. After the differential operation, the averaged measurement value of the vertical out-of-parallelism error of the vertical out-of-straightness error of the Z-slide was approximately 14 $\mu$m. For measuring the vertical out-of-parallelism $\varepsilon_{z}$, the measurement was repeated ten times with rotation speed of spindle of 5 rpm. The sampling interval was 0.006 and the effective measurement length of the roll workpiece was 100 mm. The averaged measurement value of the vertical out-of-parallelism error over ten times was approximately 12.1 $\mu$m. After the differential operation, the averaged measurement value of the vertical out-of-parallelism error was 38 nm.

Fig. 2 shows the measurement results of vertical straightness of the roll workpiece. The probes were moved by the Z-slide with a speed of 150 mm/min. The sampling interval was 5 $\mu$m and the effective measurement length of the roll workpiece was 100 mm. The measurement of vertical straightness $w(z)$ was carried out based on Eq. (9) by using the three-probe method and the reversal method. From Eq. (9) and Fig. 2, it can be seen that the vertical straightness was influenced by the vertical error motions ($e_{\perp}(z)$ and $\varepsilon_{z}$) of the Z-slide. Therefore, the vertical error motions were used to compensate for the measurement of vertical straightness. The averaged measurement value of vertical straightness over ten times was approximately 110 nm.

### 4. Conclusion

Novel algorithm for the three-probe method has been proposed for measurement of vertical straightness of a roll workpiece on an ultra-precision lathe. The measurement of vertical straightness was influenced by the vertical error motions of the precision lathe, which include the vertical out-of-straightness error component and the vertical out-of-parallelism error component. These error components were also measured by the three-probe method for compensating for the measurement of vertical straightness. Experiments have been carried out on an ultra-precision diamond turning machine with a small roll workpiece. The vertical out-of-straightness error and the vertical out-of-parallelism error over a movement range of 100 mm were measured to be 14 nm and 38 nm, respectively. The measured vertical error motions were used to compensate for the measurement of vertical straightness. Finally, the vertical straightness of the roll workpiece over a measurement range of 100 mm has been measured to be 52 nm.

### References

