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Precision evaluation of surface form error of a large-scale roll workpiece on a drum roll lathe

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ABSTRACT

This paper presents on-machine evaluation of surface form error components of a large-scale roll workpiece, including the out-of-roundness, the out-of-straightness, the taper angle and the diameter deviation, on a drum roll lathe. A pair of capacitive-type displacement probes is mounted on the carriage slide to target the two sides of the roll workpiece mounted on the spindle, which has a length of 2000 mm, a diameter of 320 mm and a mass of 350 kg. The outputs of the probes are employed to accurately evaluate the surface form error components through separating the influences of the motion errors of the spindle and the carriage slide of the lathe. It has been difficult to apply the reversal error-separation method for measurement of the out-of-roundness component of such a large workpiece because it is difficult to reverse the workpiece with respect to the spindle on the lathe due to its large size and heavy mass. An improved reversal operation technique, in which the spindle is rotated with respect to the stationary roll workpiece being held by a crane, is therefore proposed to solve this problem. Measurement uncertainty analysis is carried out to verify the reliability of the new technique for on-machine evaluation of the out-of-roundness component. The out-of-straightness component and the taper angle component of the roll workpiece are then evaluated by using a previously developed method. A simple and effective algorithm for evaluation of the diameter deviation component is also presented.

1. Introduction

Precision roll workpieces have been used as roll dies for fabrication of flat panel displays, solar cells and so on [1–5]. To fabricate large-scale roll workpieces, a large-scale ultra-precision lathes referred to as the drum roll lathes have often been used. As can be seen in specifications of the commercially available precision drum roll lathes, fabrication of a large-scale roll workpieces with a length of up to 2000 mm and a diameter of over 1500 mm is currently required [6–9]. Due to the employment of a hydrostatic spindle with a high stiffness, a large-scale roll workpiece can be rotated with a rotation speed of up to 500 rpm, while achieving a small spindle motion error on the order of 100 nm. In the roll-to-roll fabrication process, the surface profile of the roll die is transferred to the target surface. Therefore, evaluation of the surface form error components of the roll workpiece, including the out-of-straightness, the out-of-roundness, the taper angle error, and the diameter deviation, is an important task for both the quality control and compensation machining of the roll workpiece. The accuracy for measurement of the overall surface form error is required to be higher than 2 μm, in which the required accuracy for the out-of-roundness component is higher than 100 nm [10,11].

To evaluate the surface form error of a roll workpiece, commercial surface form measuring instruments, which can evaluate the surface form error of the roll workpiece with sub-micrometer accuracy, are well used [10,12,13]. These instruments can evaluate not only the out-of-roundness and the out-of-straightness but also the diameter deviation of the roll workpiece. Some commercial instruments with specified designs can measure the roll workpiece with a diameter of 500 mm, a length of 1000 mm and a mass of 800 kg [13]. However, it is necessary to remove the roll workpiece from the drum roll lathe and then to mount it on the rotary table of the measuring instrument so that the surface form error can be evaluated. This is a heavy task. Alignment of the center axis of the roll workpiece to that of the rotary table is also time-consuming. In addition, there are no commercial measuring instruments that can measure a large-scale roll workpiece with a length of up to 2000 mm.

A more realistic way is to carry out the measurement on the roll drum lathe where the roll workpiece has been turned. This can be done by simply mounting displacement probes on the tool

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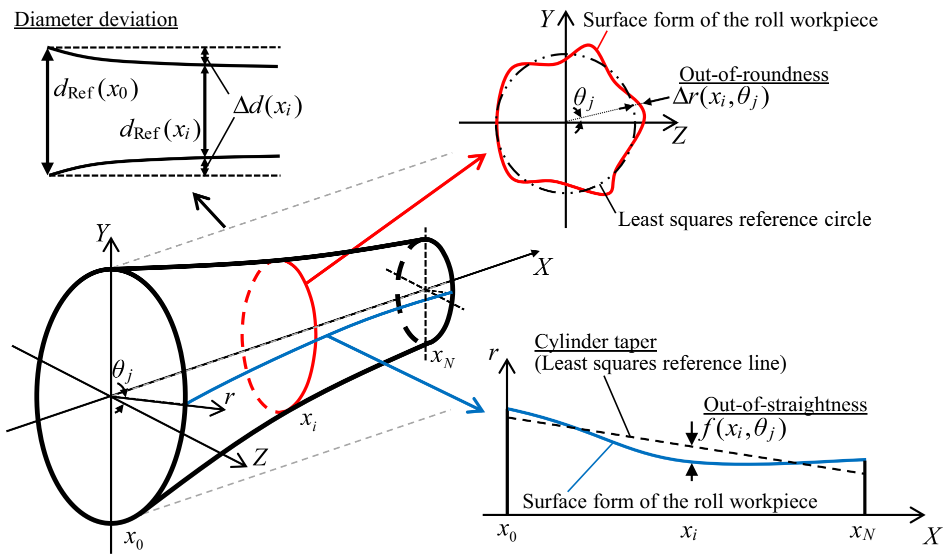

Fig. 1. Schematic of a surface form of a roll workpiece.

post of the lathe so that the roll workpiece can be scanned with the displacement probes [14–19]. Since the center axis of the roll workpiece is self-aligned to that of the spindle after the turning process, the time-consuming alignment process required for the measurement on the form measuring instruments can be avoided. On-machine measurement is also effective for the compensation machining of the roll workpiece.

For the surface form measurement on the drum roll lathe, the scanning motions along the circumferential and axial directions of the roll workpiece are generated by the spindle and the carriage slide of the drum roll lathe, respectively. Based on the fact that amplitudes of the surface form error of the roll workpiece and the motion errors of both the spindle and the slide are on the same order [14], the first priority for accurate on-machine form error measurement is to separate the motion errors from the form error, which are included in the outputs of the displacement probes, by using the error separation methods such as the reversal error-separation method and the multi-probe method [15–20]. Compared with the multi-probe method, the reversal error-separation method is much simpler and has less data processing errors, and therefore suitable for measurement on an ultra-precision machine tool such as the drum roll lathe with highly repeatable machine motions.

In the previous work by the authors, the reversal error-separation method was applied for accurate measurement of the motion error of the carriage slide of a drum roll lathe so that the influence of the out-of-straightness component of the roll workpiece used as the specimen for the measurement could be removed [11,21]. The out-of-straightness component and the taper angle of the roll workpiece can also be measured by the same method. In the measurement, the roll workpiece was rotated 180° with respect to a pair of displacement probes as the reversal operation for the reversal error-separation method. This could be easily done by using the spindle of the drum roll lathe, on which the roll workpiece was mounted. On the other hand, however, when the reversal method is applied for the measurement of the out-of-roundness component of the roll workpiece, the roll workpiece is required to be rotated 180° with respect to the spindle [16–18,22–24], which is the necessary reversal operation for removing the influence of the spindle error. Taking into consideration the size and mass of the large-scale roll workpiece, it is extremely difficult and also dangerous for the operator.

In this paper, an improved reversal operation is proposed so that the reversal error-separation method can also be applied for accurate measurement of the out-of-roundness component of the large-scale roll workpiece on the drum roll lathe where a pair of displacement probes is mounted on the carriage slide to target the two sides of the roll workpiece. In the improved reversal operation, the spindle is rotated 180° with respect to the roll workpiece being held stationary by a crane. The out-of-roundness component can be accurately evaluated from the outputs of the two probes before and after the improved reversal operation. Meanwhile, the same probe setup can be employed for measurement of the out-of-straightness component and the taper angle of the workpiece with the previously developed method [11], as well as the diameter deviation of the roll workpiece with a simple evaluation algorithm. After a description on the measurement principles for the surface form error components, experiments on a large-scale drum roll lathe are described. Measurement uncertainty analysis is also presented to demonstrate the reliability of the proposed improved reversal operation for measurement of the out-of-roundness component.

2. Measurement principle

2.1. Measurement of the out-of-roundness component

An improved reversal operation technique is proposed for applying the reversal error-separation method to the measurement of the out-of-roundness component of a large-scale roll workpiece. A schematic model of the surface form of the roll workpiece is shown in Fig. 1. The out-of-straightness and the out-of-roundness are the two main components of the surface form error [25]. The out-of-straightness component $f(x_i, \theta_j)$ is the deviation from a reference line, which is determined as a least squares reference line obtained from a sectional profile of the roll workpiece along the axial direction [26]. In the same manner, the out-of-roundness component $\Delta r(x_i, \theta_j)$ is the deviation from a reference circle, which is determined as a least squares circle obtained from a sectional profile of the roll workpiece along the circumferential direction [27]. In addition, the cylinder taper component is another parameter of the surface form error of the roll workpiece. The cylinder taper component, which represents the degree of the taper shape of the roll