Study on compensation of tool position error during tool rotation for ultra-fine planing of micro angle-variable patterns

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Abstract

A machining tool is installed at an ultra-fine machining system before performing a planning process. The vertical axis of the system and the tool centre line should be overlapped; however, the two lines usually have a gap along the horizontal direction (y-axis) because the tool is manually installed. This gap called ‘tool setting error (eys)’ can make severe errors along the y-axis (pitch) and z-axis (depth) especially in the micro-scale when rotating the machine. Therefore, these errors were analyzed based on their geometric relationship, and the micro angle-variable patterns having different tool rotation angles were machined in this study. Before tool setting error compensation, machined prism patterns had over 50 micrometer errors. After tool setting error compensation, micro angle-variable prism patterns were precisely machined (under 1 micrometer error).

1. Introduction

The display market is rapidly growing based on the increase of 3D contents such as broadcasts, movies and advertisements. There are many studies related to core component manufacturing technologies for 3D display implementation. 3D display is the technology of conveying depth perception to the viewer by means of stereopsis for binocular vision. Glasses for 3D display have usually been used for increasing the
depth perception; however, 3D technologies without glasses have recently been studied in order to remove the inconvenience of wearing glasses. Among 3D implementation methods without glasses, optical modulation method has merits such as less degradation of resolution and luminance. For improvement of optical efficiency by using the optical modulation method, micro variable angle prism patterns are needed [1-2].

The micro prism patterns can be fabricated by using chemical and optical methods as well as by using a mechanical method with diamond tools. The mechanical method with the diamond tools could easily make the patterns with high quality and has the advantage of mass production. However, a tool rotation axis should be added for angle-variable prism patterns machining if using the mechanical method, and machining errors could occur due to tool setting error. In the present study, these errors caused by tool setting error were analyzed, and the tool position for micro angle-variable patterns having different tool rotation angles was compensated.

2. Variable types of errors according to tool setting and rotation

A tool setting error from the discordance between tool axis line and tool centre line usually occurs because the tool is manually installed in an ultra-precise multi-axis machining system while tool setting, as shown in Figure 1 [3].

![Figure 1 The variable types of errors caused by tool setting and tool rotation](image)

The tool setting error usually occurs along the horizontal direction, and it generates two types of additional errors during tool rotation: a horizontal error \(e_{ys} \cdot \cos \theta\) and a vertical error \(e_{ys} \cdot \sin \theta\). The total errors of the horizontal axis and vertical axis are
functions of the tool setting error, the tool axis radius \( r \) and the tool rotation angle \( \theta \) and can be expressed as follows:

\[
e_{z,\text{total}} = (1 - \cos \theta) \cdot r + \sin \theta \cdot e_{ys} \tag{1}
\]

\[
e_{y,\text{total}} = \sin \theta \cdot r + (\cos \theta - 1) \cdot e_{ys} \tag{2}
\]

where \( e_{z,\text{total}} \) is the total error of along the \( z \)-axis, and \( e_{y,\text{total}} \) is the total error of along the \( y \)-axis. The \( e_{z,\text{total}} \) means the difference of the \( z \)-coordinate values between \( \theta_1 \) (generally \( \theta_1 \) is zero) and \( \theta_2 \), and should be measured two times with different values of \( \theta_2 \) (for example, \( \theta_2 \) is 10 degrees and 20 degrees). The two unknown constants \( r \) and \( e_{ys} \) in Equation (1) can be obtained by these two simultaneous equations. Equation (2) can be also solved inputting the obtained two constants. Based on this analysis, the total errors of the horizontal axis and vertical axis can be calculated at any tool rotation angle, and the tool position can be also calibrated when the micro angle-variable patterns are machined.

3. Angle-variable prism patterns machining and discussions

Experiments were conducted on machine variable-angle prism patterns by using a 4-axis ultra-precision machine tool with a tool rotation axis. A tool dynamometer was employed on the tool axis in order to measure the cutting force and tool touch. The angle-variable prism patterns were machined with and without tool setting error compensation, and the results were compared. The tool rotation angle was increased from 0° to 20° at interval of 1°, the depth of cut was 10\( \mu \)m, and the pitch was 20 \( \mu \)m. The cutting speed was 12,000mm/min and a 90° diamond prism tool was employed. The two unknown constants \( r \) and \( e_{ys} \) were obtained by measuring \( e_{z,\text{total}} \) five times with different values of \( \theta \) (0, 10, 20, 30, and 40°) by using Equation (1). The \( r \) and the \( e_{ys} \) were 120.555mm and -0.178mm.

Figures 2 (a) and (b) show the machined results of angle-variable prism patterns without and with tool setting error compensation, respectively. The depth of cut of angle-variable prism patterns was increased without tool setting error compensation, as shown in Figure 2 (a), because the \( e_{ys} \cdot \sin \theta \) of Equation (1) makes an increase in the depth of cut. Otherwise, the depth of cut (under 1 micrometer error) of angle-
variable prism patterns was constant and precise with tool setting error compensation, as shown in Figure 2 (b). The result shows that tool setting error should be compensated.

Figure 2 The final machining results of angle-variable patterns (a) without and (b) with considering tool setting error

4. Conclusions
In the present study, tool position error with discordance between the tool axis line and tool centre line was geometrically analyzed and calibrated. Tool setting error can make severe error (especially along the Z-axis) when machining the angle-variable prism patterns. Tool setting error was calibrated, and the angle-variable prism patterns (0-20° and depth of cut 10 µm) were constantly and precisely machined under 1 micrometer error.

References: