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An on-machine error calibration method for a laser micromachining tool

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ABSTRACT

In this paper, an on-machine error calibration method, covering error modeling and measurement, is proposed to evaluate and compensate the errors caused by the mechanical and optical system equipped in the micromachining center using the femtosecond laser. Through preliminary tests by dicing silicon wafer, it has revealed that the squareness, laser beam misalign and focal position offset, are the main causes to result in the inaccuracy of micromachining. Consequently, an error modeling method is proposed to evaluate the error distribution in the workspace, and hereafter a comprehensive error vector of the laser beam, combining the squareness errors of Z-axis with the laser beam misalign, is generated by the variable substitution method. Subsequently, an increment error model in the instant local coordinates is established to satisfy the requirement of the programming method commonly used in the laser machine tools. Furthermore, a series of holes and grooves are machined on the femtosecond laser micromachining center to validate the proposed approach and model. The machining dimensions including diameters, distances and angles, are measured on-machine to identify the squareness errors, laser beam misalign and focal position offset according to the proposed error model. Finally, the experimental results show that, comparing to the uncompensated tests, the machining accuracy has been significantly improved with the proposed method.

1. Introduction

The femtosecond laser utilizes ultrashort laser pulse ablation properties to achieve a fine solution in machining desired microstructures. The material is ablated by such a short time scale that virtually there is significantly smaller heat transfer to the surrounding areas than processing with picosecond or longer pulses, and hence the ultra-fast laser machining is also well known as a cold machining technology without collateral damage to the surroundings [1,2]. This cold machining technology increases dice strength and reduces debris and contaminations. Therefore, the femtosecond laser is becoming a powerful tool in micromachining, such as wafer dicing [3,4], microfluidic [5,6], etc.

During the micromachining process, the optical system, including lens, reflector, attenuator, and so on, is utilized to deliver, adjust and finally focus the laser beam through an objective on the sample surface. Meanwhile, the mechanical transition system, normally consists multiple linear and rotary axes, is applied to generate scanning path. Inevitably, in the optical system, the laser beam misalign, appears when the optical components are set and adjusted, and the focal position offset arises resulted from the dispersion effect. The transferring and positioning errors exist for the inaccuracy of mechanical system when the movement stages are manufactured and assembled. They both contribute to the inaccuracy of micromachining center using laser. Presently, the accuracy of the micro machine tool has been extending to the scale of submicrometer or even to the scale of nanometer. This presents a great challenge for designing, manufacturing and maintaining the mechanical and optical system equipped in a micro machine tool using laser. It means that a higher accuracy motion control system, a better using environment, and a more skillful operator are needed. Unfortunately, this type of high precision mechanical and optical system, well controlled machining environment and skillful operator are either unavailable or very expensive. Thus, to find an economical and effective method to improve the micromachining accuracy under the current machining settings, in a normal workshop environment and with a reasonable operator is critical for micromachining technology applied in practice.

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Similar to the ordinary machine tool, the geometric [7,8], heat [9] and non-rigid errors [10] are the main sources resulted in the inaccuracy of a micro machine tool. They take a different part in the errors of various types of micro machine tools. In the previous researches, they reported that the thermal deformation of the high speed spindle equipped in a micro machine tool was the major impaction on the machining error. In a micro milling machine, it has been found that the limited stiffness of a tiny tool mainly contributed to the inaccuracy of machining parts. Generally, the geometric error is considered as the primary cause to result in the deviation between the machined and designed surface of the workpiece. Then, an error model can be established to evaluate the error distribution of a micro machine tool. The model is normally established using HTM (Homogenous Transformation Matrices) [11,12], D-H (Denavit–Hartenberg) [13], MD-H (Modified Denavit–Hartenberg) [14] or MBS (Multi-Body System) [15] to describe the error of cutter location and tool orientation between the workpiece and the machine tool. These methods have also been applied in the micro machining area. A micro v-groove machine tool, for instance, is viewed as a multi-body system and an error model is proposed to estimate the machining error in the Z-axis direction [16]. The performance of five-DOF motion in ultraprecision linear stage is evaluated by using HTM [17]. Actually, these models are built on the mathematical basis of HTM, except the origin and direction setting of local coordinates for each axis. As to error modeling process and complexity, there is no essential difference between them. However, a micro machine tool is generally designed using a self-develop CNC system to meet the demand of special machining purpose. It means that the programming method and operation mode are different from the commercial ones available on the market. Especially in the micro machine tool using laser, the increment programming method is preferred in defining the motion of the stages after an initial position of the laser is selected to set a local coordinates, other than a global coordinates needed by the common modeling method.

Due to the very limited range of the motion axes equipped in a micro machine tool, the current error measurement instruments used in the industry, such as laser interferometer and double ballbar, could not be fitted into such a tight workspace. Hence, these measurement methods are not appropriate for the micro machine tools. A prefer method for measuring the error of a micro machine tool should be implemented on-machine. It is a feasible way to measure the error on-machine using some miniature sensors with a high precision. A capacitance sensor based multi-degree-of-freedom measurement system has been developed for measuring geometric errors of a miniaturized machine tool overcoming the size limitations. Five volumetric errors that are position dependent when every component moves along an axis, and three squareness errors that are position independent when the movements of components are not perpendicular to each other, were achieved by the proposed method [8]. It has been reported that a high-precision displacement sensor, was employed to eliminate the profile error caused by the re-installation of the workpiece in an ultra-precision grinding machine [18]. Also, a two-ball gage method by means of electrical contact was developed to analyze the geometrical errors in micro machine tools [19]. A novel measurement method integrating machine vision was proposed to measure the machining error on-machine [20]. Meanwhile, the error of the machining part caused by the inaccuracy of a micro machine tool could be applied to identify the geometric errors. In an on-machine method, the tilt angle of the intersection curve of two toruses generated from two neighboring rotary cuts in an ultra-precision raster milling was measured to identify the spindle inclination error [21]. Another paper presented a single kinematic errors accurate fitting methodology for the micro v-groove machine tools [16]. However, a micro machine tool using laser is quite different from the ordinary ones as the tool is invisible. The present approaches are not applicable for measuring and identifying the error resulted from the combination of the mechanical and optical system.

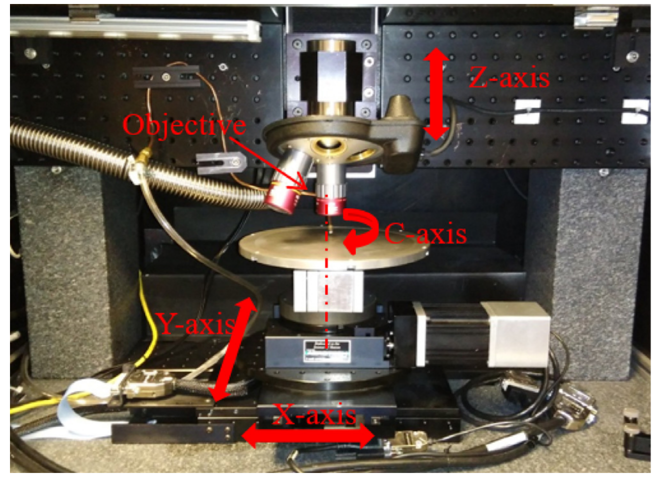

Fig. 1. Micromachining center involving a rotary table.

Hence, how to model and measure the errors of a laser micromachining center, is becoming an obstacle to further improve the micromachining accuracy. A simple, reliable and highly efficient measurement and compensation method is urgently needed to diagnose and evaluate geometric error of a micro machine tool to satisfy the increasing high precision demand in the modern industry and scientific research. In this paper, it has been found that the squareness errors caused by the inaccuracy of mechanical system, laser beam misalign and laser focal position offset resulted from the error of optical system, mainly contribute to the machining error according to a test of silicon wafer dicing. Then, an increment modeling method using differential transformation theory is proposed to evaluate the error distribution in the instant local coordinates. Due to the linear relationship between the squareness errors of Z-axis and the laser beam misalign, they are merged into a compressive error vector by the variable substitution method. Furthermore, an on-machine method is developed to identify the errors both in mechanical system and optical system according to the proposed error model. First, a precision rotary stage is applied to measure the squareness error of Y-axis with respect to X-axis. Then, two grooves are machined with the scanning path along X-axis and Y-axis in turn, and the angles between each groove and X-axis or Y-axis are denoted as the compressive error of the laser beam. Additionally, a mark hole is ablated at the focal position of visible light, while a serials of holes are machined along X-axis at various focal positions of the laser beam. Thus, the focal position offset could be represented by the distance between the mark hole and minimum one in the series. Finally, a series of experiments are conducted on the micro machine tool using femtosecond laser to test and verify the proposed method.

2. Geometric error modeling

2.1. Problems caused by wafer dicing

In a practical task of silicon wafer dicing, the diameter of the wafer is Φ100 mm and thickness is 600 μm, while the space between two devices on the wafer is only 300 μm. A self-developed micromachining center using femtosecond laser (as shown in Fig. 1) is used to conduct this wafer dicing task. There are four movement axes, including three translational axes (X-axis, Y-axis and Z-axis) and a rotary axis (C-axis). Among them, X-axis and Y-axis shift the worktable, Z-axis controls the focal position, while C-axis is applied