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# An in-process measurement method for repair of defective microstructures by using a fast tool servo with a force sensor

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ABSTRACT

This paper presents an in-process measurement method, which is capable of conducting real-time position identification and on-machine profile characterization of micro-defects in defective microstructures by using a fast tool servo with a force sensor (FS-FTS) on an ultra-precision lathe. A real-time thrust force map is captured in the process of cutting the microstructures by the FS-FTS to indicate the cutting status with respect to the cutting tool position in the coordinate system of the lathe. Based on the thrust force map, the positions of the defects are identified in real time from the locations of the abnormal variations in the map associated with the occurrences of the defects. Characterization of the defects is then conducted by employing the force-controlled cutting tool as the measuring probe to measure the sectional profiles of the defective microstructures. The identified positions and the characterized profiles of the defects are then fed back to carry out the repair fabrication of the defective microstructures with an accurate tool path. Experiments of in-process detection and repair of the micro-defects in the microstructures over the outer surface of a roll mold were carried out to confirm the feasibility of the proposed method.


## 1. Introduction

As one of the microcutting technologies [1,2], the fast tool servo (FTS) [3,4] is employed on an ultra-precision lathe to manufacture complex microstructured surfaces, such as micro-prisms [5], microlenses [6], microlens arrays [7,8], sinusoidal grids [9], compound eye freeform surfaces [10], and diffractive optical elements (DOEs) [11,12]. It is expected to play an important role in fabrication of large-sized master molds with microstructures, such as roll molds or wafer-level molds, for mass replication of surfaces with optical functions [13]. The fabricated microstructured surface of such a master mold is required to have a sub-micrometric form accuracy and an optical surface quality with zero or minimum defects [14,15].

Meanwhile, the FTS-based microcutting is a complicated process in which material is removed at a high rate by a single-point diamond tool with a very sharp edge [16]. Although the advanced FTS systems and the ultra-precision lathes have been well developed to achieve sub-micrometric or even better positioning accuracies, the cutting process is affected by a number of factors in mechanical, thermal and chemical aspects [17]. Defects such as burrs, voids or bumps can be caused by tool–chip adhesion, tool chatter, tool wear, etc. [18,19], especially when microstructures are cut on hard materials. Improper setting of cutting parameters such as cutting fluid mist can also lead to the formation of defects. The fabrication of a large-sized master mold is a very time-consuming process, which can last for a couple of days. It is difficult to maintain a constant cutting status throughout the process. There is thus a high possibility for micro-defects to occur in the midst of the process [20]. A post-process inspection of micro-defects on the master mold surface is carried out as the quality assurance test. However, there have been no ways to repair the micro-defects, although it is desired from the point of view of the extremely high cost of the master mold.

On the other hand, repair of micro-defects on photolithographic masks is a common process in semiconductor industry. The repair is typically carried out by using an electron beam (EB) [21]. In an EB repair process, a high-energy scanning electron beam in an EB equipment is employed to induce a local chemical reaction on the defective region of the mask surface [21]. Before the repair, the position and the profile of the defect on the mask are detected through scanning the same electron beam with a low energy setting over the entire wafer surface in the EB equipment. Because the same electron beam is used as the measuring probe for the detection and

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as the tool for the repair, the coordinates of the measuring probe are identical to those of the fabricating tool, resulting in an accurate repair of the defects.

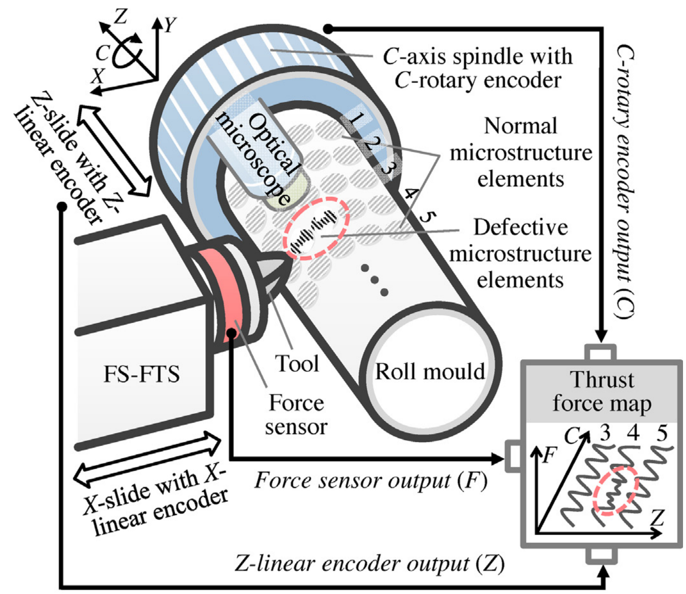
The motivation of this research is to realize the repair of a micro-defect in a defective microstructure of the large-sized master mold fabricated by FTS on an ultra-precision lathe. As can be seen from the above case of photolithographic mask repair, it is necessary to develop a measurement technology that can address the next two important issues. The first issue is the detection of position and profile of the micro-defect over the entire surface of the mold in a short time. The second issue is the feedback of the measured information to the FTS on the ultra-precision lathe for generating an accurate repair cutting path. The measurement technology is thus required to have a high measurement speed and sub-micrometric resolutions in both vertical and lateral directions. The coordinate systems for the measurement and the repair cutting are also needed to have sub-micrometric correlations with each other so that the repair cutting can be made exactly against the micro-defect without influencing other parts of the mold surface. There are surface metrology-based methods existing for detection of the positions and profiles of defects on ultra-precision surfaces, such as the laser scattering method [22], interferometers [23], scanning probe microscopes (SPM) [24,25], confocal microscopes [26], contact thermal sensors [27] or optical sensors [28]. Some of them with special designs can be set up on an ultra-precision lathe for on-machine measurement. However, the field of view of such a measuring instrument is very small, typically less than 1 $mm^2$, for getting a sub-micrometric lateral resolution. This makes the micro-defect detection process on a large-sized master mold, typically with an area over 100 $mm^2$, extremely time-consuming. It is also a difficult task to make sub-micrometric correlation of the coordinate system of the measuring system with that of the FTS on the ultra-precision lathe.

Various sensors have been employed to monitor the cutting process [29,30]. Among the measurable process variables, the cutting force is a good indicator of the cutting status and an important physical parameter for understanding the cutting phenomena [31,32]. The formation of a defect, which causes a variation in the cutting force, can be detected in real time by making in-process force measurement with a direct linkage to the machine coordinate system [33]. Taking into consideration the small amplitude of the cutting force in the FTS-based microcutting, it is desired to set the location of a sensitive and stiff force sensor to the cutting point as close as possible. This has been achieved in a force sensor integrated FTS developed by the authors, which is referred to as the FS-FTS [34]. It has also been demonstrated that the FS-FTS has the ability of making profile measurement of the machined surface by using the cutting tool as the measuring probe [35]. It is expected to utilize this function for characterization of the surface profile of the micro-defect on the master mold.

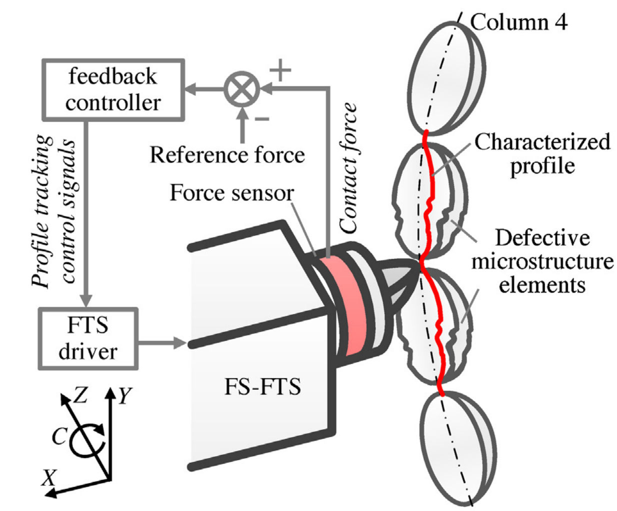
In this paper, a new in-process measurement method for the purpose of repairing defective microstructures on an ultra-precision lathe is proposed based on the abilities of the FS-FTS for real-time cutting force measurement and on-machine profile measurement. Experiments of in-process measurement and repair of micro-defects with dimensions on the order of 1 μm on a roll mold are carried out. The principle of the proposed method and the experimental results are presented.

## 2. Principle

There are two parts in the process of measurement and repair of defective microstructure elements. The first part, which is composed of two steps (Steps 1 and 2) shown in Fig. 1, is related to the in-process measurement method. The second part, which is also composed of two steps (Steps 3 and 4) shown in Fig. 2, is related to the repair process.




(a) Step 1 for real-time detection of the micro-defect positions




(b) Step 2 for characterization of the micro-defect surface profiles

**Fig. 1.** Steps of the in-process measurement method for repair of destructive microstructures on a roll mold. (a) Step 1 for real-time detection of the micro-defect positions. (b) Step 2 for characterization of the micro-defect surface profiles.

As can be seen in Fig. 1(a), the FS-FTS is mounted on a three-axis ultra-precision lathe for in-process measurement and repair of micro-defects on a roll mold. The roll mold is a cylindrical workpiece on which microstructure elements are fabricated by the FS-FTS. The workpiece is vacuum-chucked on the *C*-axis spindle with its rotation about the *Z*-axis. A *C*-rotary encoder is equipped with the spindle for rotational positioning. The *C*-axis spindle can be moved along the *Z*-axis by the *Z*-slide. The FS-FTS, with a piezoelectric-type force sensor integrated with the tool holder, is mounted on an *X*-slide to generate the fast in-feed motion of the tool along the *X*-direction. The position of the *X*-side and the *Z*-slide are measured by the *X*-linear encoder and the *Z*-linear encoder, respectively. During the cutting, the fast in-feed motion of the tool is generated by the FS-FTS in responding to the output pulse of the *C*-rotary encoder, in this case the tool servo motion with the *C*-directional rotation of the *C*-axis spindle can be synchronized. By combining the *X*-directional fast in-feed motion, the *Z*-directional