

# CHARACTERIZATION OF ERRORS AFFECTING SURFACE GENERATION IN FAST TOOL SERVO (FTS) MACHINING

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## ABSTRACT

In this paper, a study of the fabrication of optical microstructures by fast tool servo (FTS) machining technology is presented. The study started from locating the sources of error exclusively involved in ultra-precision machining with FTS, which are stroke error, spatial error, trajectory generation error and errors of cutting parameters such as spindle speed, depth of cut, feed rate, etc. Hence, a series of cutting tests and analyses have been carried out to characterize the systemic error of FTS system. The results show that stroke movement is one of the factors affecting the form accuracy of machined profile.

## INTRODUCTION

Nowadays, the use of display system in photonics products is increasing; optical microstructures such as micro-lens arrays are widely used critical components in the display system. One of the supreme methods which are commonly used in the fabrication of optical microstructures is ultra-precision machining with fast tool servo (FTS). The FTS is an independently operated positioning device which is usually mounted onto ultra-precision machines for increasing the tool positioning accuracy in order to fabricate optical microstructures by the rapid actuation of tools with fine resolution, positioning accuracy, and sufficient high bandwidth [1].

Although there has been extensive research work on the design and control of tool actuators for FTS machining [2-5], relatively little work has been reported in the studies of nano-surface generation in FTS machining of optical microstructures. There is a need to study on the optimization of the cutting conditions and minimizing the errors in FTS machining of optical microstructures. As a result, this paper presents a study of the fabrication of optical microstructures by FTS.

### Factors affecting surface generation

To study the fabrication of micro-lens array by FTS machining, the first step is to identify the

factors affecting the surface generation. Based on the literature presented in the last decade, FTS machining is the technology which is developed based on single-point diamond turning technology. The material removal process is governed by the ultra-precision machine characteristics, tools and lubrication, environmental condition, machining parameters, surface defects and morphological characterization of samples. The machining parameters include rotational spindle speed, feed rate, depth of cut and material of samples while the morphological defects could be distinguished into four types, which are waviness due to vibration, stria or tool mark created by diamond tools, cracks due to material structure and variation of form and position.

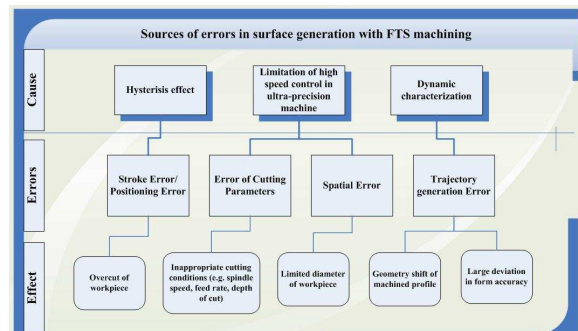


FIGURE 1. Sources of errors in surface generation with FTS machining.

Figure 1 shows the sources of errors exclusively involved in surface generation with FTS machining. It is well known that piezoelectric actuator is often used for the purpose of micro-positioning and active control. However, one of the drawbacks of the piezo actuators is the existence of hysteresis which leads to oscillation and vibration [6]. Eventually, stroke error or positioning error would happen and there exist over cut phenomenon on the fabricated profile. On the other hands, the limitation of ultra-precision machine also leads to error of cutting parameters and spatial error which limits size of the workpiece. For example, the surface roughness of fabricated profile could be

enhanced by employing spindle speed in SPDT technology. When designing the machining conditions employed in FTS machining, it could hardly simply increase the spindle speed for better surface finish because of the limitation of the bandwidth of the FTS actuator.

In FTS machining, the rotational and linear sensor feedback the real-time position of the spindle and diamond tool for DSP (digital signal processor) Kernel to calculate the location being cut in the next moment. This calculation is according to the program of the geometry of desired profile preset in SOP control system. Figure 2 shows the signal processing in FTS machining. The final source of error to be mentioned is dynamic characterization which leads to trajectory generation error. This error could also be mentioned as improper computing of the cutting position in real-time which always induces geometrical shift of machined profile and large deviation in form error.

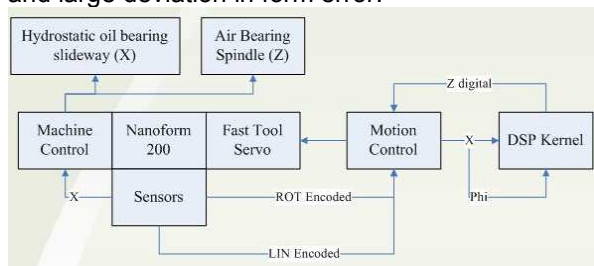


FIGURE 2. Signal processing in FTS machining

### Characterization of systematic errors

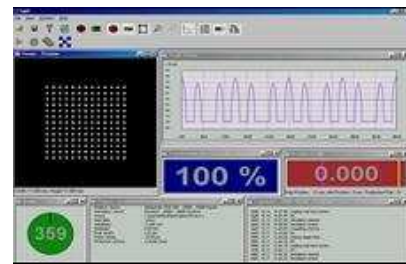
To investigate the highlighted errors exclusively for FTS machining, a series of cutting tests was carried out on Nanoform 200 ultra-precision machine incorporated with a FTS system located in Advanced Optics Manufacturing Centre (AOMC) of The Hong Kong Polytechnic University (see Figure 3). FTS driven by a piezo-electric actuator is mounted on the Z-slide of the lathe, which enables the diamond tool to cut back and forth in 1000 Hz bandwidth of natural frequency. The FTS control system receives input from work spindle and slide, the tool position can be calculated in real-time and commanded in order to move the tool accordingly.

### Proposed methodologies on characterization of systematic errors

The first step to investigate the fabrication process of complex regular micro-structural pattern (e.g. microlens array as shown in Figure 4), the study was proposed by starting from the fundamental level – flat surface.



(a) Nanoform 200 ultra-precision machine



(b) User interface of FTS control system

FIGURE 3. Fast tool servo machining system

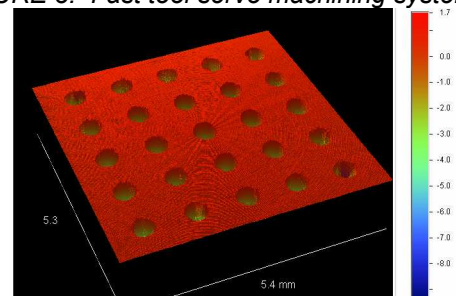


FIGURE 4. Fabricated optical microstructure

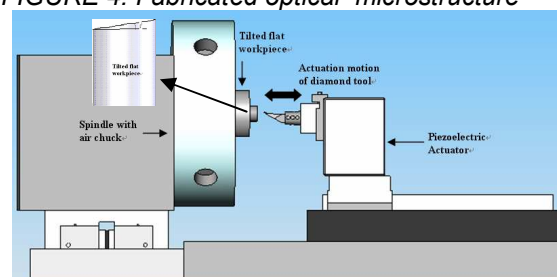


FIGURE 5. Fabrication of tilted flat surface by ultra-precision machining with FTS

To test the performance of FTS machining technology, tilted flat surface (see Figure 5) is machined since flat surface helps to minimize the geometric error involved and is easier to be measured. In cutting tilted flat surface, the FTS is required to drive the tool to move in a sinusoidal trajectory at full amplitude.

On the other hands, the effect of spatial error can be investigated by conducting cutting tests on samples with different diameters and small gradient. This can minimize effect of other

cutting conditions and help to determine the spatial error quantitatively. Hence the geometrical error is determined. Single spherical surface would be proposed as the geometry of cut. Figure 6 shows the spherical profile machined by FTS machining technology. The results would be used to further study the surface generation of optical microstructure with FTS machining.

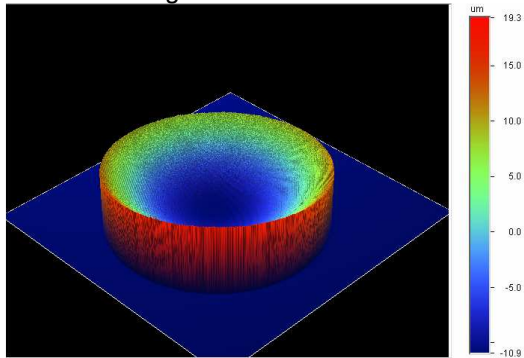


FIGURE 6. Spherical profile machined by FTS machining technology.

#### Determination of optimal cutting parameters

To increase machine or process efficiency, the determination of optimal cutting process parameter settings is a key factor and a number of mathematical models and techniques have been proposed and effectively used to achieve this objective. One of the most popularly adapted methodologies named Taguchi method is used in the present study for optimizing the cutting conditions of tilted flat surface with FTS machining. The selected process parameters affecting surface generation in FTS machining include radius of diamond tool, spindle speed, feed rate, and depth of cut.

Accordingly, four controllable 3-level factors and two response variables are proposed in the present study. Table 1 tabulates the four factors of spindle speed (rpm), feed rate mm/min), depth of cut rate ( $\mu\text{m}$ ), and radius of diamond tool (mm) with three levels in this study. Namely, the experimental work is based on the orthogonal array L9(3<sup>4</sup>). The two response variables include surface roughness mean and form accuracy in the fabricated tilted flat surface. To investigate the stroke error, cutting testes were carried out by presetting range of actuation so as to determine the error from the motion of stroke or travel of actuator with 5  $\mu\text{m}$  of depth of cut. To test the positioning accuracy of the FTS, full range of displacement of the actuator (i.e. 30  $\mu\text{m}$ ) have been used. Figure 7 shows

the schematic illustration of regional analysis of stroke error. It can be seen that stepping height of each zone is 5  $\mu\text{m}$ , which is also the Z-axis feed after each round of machining. This means that a total of 6 rounds of machining is needed to cut a component of 30  $\mu\text{m}$  in depth. And full stroke of each zone is changing from the lowest 5  $\mu\text{m}$  of zone 1 to the highest 30  $\mu\text{m}$  of zone 6.

Table 1: Experimental factors and factor level

Level of experimental factor	Experimental factors			
	A(rpm)	B(mm/min)	C( $\mu\text{m}$ )	D (mm)
1	50	0.25	5	0.02
2	75	0.5	10	0.03
3	100	0.75	15	0.04

Table 2: Orthogonal array L<sub>9</sub>(3<sup>4</sup>) of the experimental runs

L9	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

#### Analysis of stroke error

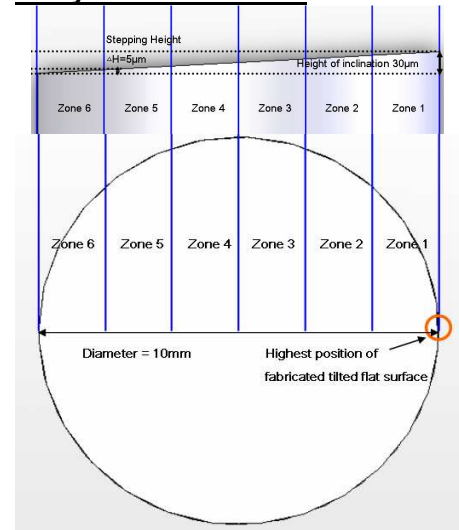


FIGURE 7. Schematic illustration of regional analysis of stroke error

To analyse the stroke error of machined profile regionally, the machined profile was measured across the diameter of fabricated tilted flat surface from the highest position to the lowest. And then the measured surface should the most

oblique ranged  $30 \mu\text{m}$ . Afterwards, the measured data of tilted flat surface would be equally divided into six zones. The depth of cut in machining is  $5 \mu\text{m}$  for each round of cut. By an analysis of the form error of equally distributed zone, stroke error of different travel ranges of the FTS can be determined. Then the measured data are analysed zone by zone by removing the tilted form for determination of the form error in specific zone.

Zone	Stepping Height ( $\mu\text{m}$ )	Stroke of FTS ( $\mu\text{m}$ )	Form Error ( $\mu\text{m}$ )
1	5	5	0.6175
2	5	10	0.5823
3	5	15	0.5835
4	5	20	0.6073
5	5	25	0.6229
6	5	30	0.6801

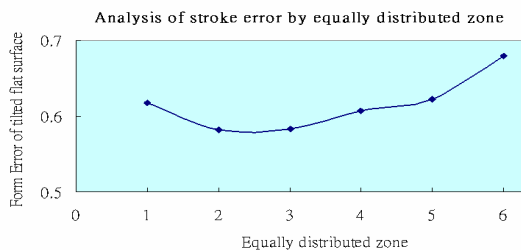


FIGURE 8. Results of form analysis in specific zone.

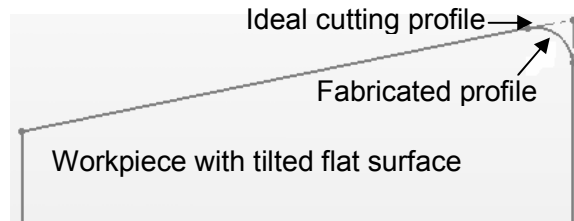


FIGURE 9. Graphical illustration of over cut phenomenon happened in FTS machining of tilted flat surface.

Figure 8 shows the results of form analysis in specific zones. In the plot of the stroke error in equally distributed zone, it is interesting to note that there exists a trend that form error increases with increasing range of travel except zone 1. Since a larger travel range of the FTS demands the actuator to drive the diamond tool forth and back, this leads to larger form error. The exception case of zone 1 can be explained by the overcut phenomenon which happens in each cut and affect the form error of zone 1 significantly when employing high stroke such as

$30 \mu\text{m}$ . Figure 9 shows the graphical illustration of the over cut phenomenon happened in FTS machining of tilted flat surface.

## CONCLUSION

This paper presents methodologies and experimental work for the characterization of errors affecting surface generation in FTS machining. The errors are associated with the material removal process which is governed by the ultra-precision machine characteristics, tools and lubrication, environmental condition, machining parameters, surface defects and morphological characterization of samples. A series of cutting experiments have been conducted. It is interesting to note that high stroke movement is prominent for affecting surface generation in FTS machining and this significantly affects the form accuracy of the workpiece being cut.

## ACKNOWLEDGEMENT

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