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A comprehensive error correction/prediction system for tool-servo driven diamond turning of freeform surfaces

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Abstract
Slow tool servo (STS) is widely used to fabricate freeform optical elements. However, it is still difficult to obtain nanometer-level form accuracy in a short time due to characteristic error factors such as the tool trajectory error and the dynamic follow-up error of machine tools. In this study, we proposed a new machining flow, which included error factor modification and error prediction, to improve the form accuracy in machining freeform surfaces by STS. Comprehensive error analysis and modelling was performed to identify all the main error factors, some of which have never been taken into account by previous researchers. Numerical simulation was then carried out to clarify the relationship between these error factors and the form error of the finished surface. Using the proposed error correction/prediction system, fabrication of micron-level sinusoidal wave grids was attempted on single-crystal silicon. The form accuracy was successfully improved to the nanometer-level.

Keywords: freeform surface, ultraprecision machining, diamond turning, slow tool servo, sinusoidal wave grid, single crystal silicon

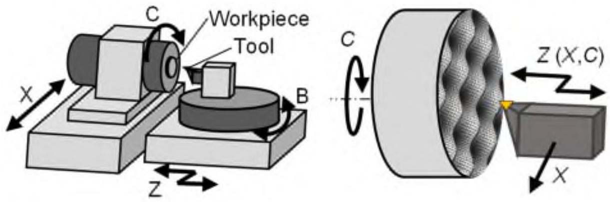
1. Introduction

Slow tool servo (STS) is an effective solution to the machining of freeform optical elements. It enables fabricating freeform surfaces in less time compared with milling or fly cutting [1]. In machining freeform surfaces by STS turning, a number of factors cause form errors of workpiece. A few previous researches have analysed the effect of some individual error factors [2], however there is no available literature on the comprehensive analysis and compensation of all the error factors. In the conventional machining flow, only some specific error factors are considered with a feedback correction system in which machining-correction cycles are repeated until the required form accuracy is obtained. Thus, it is extremely difficult and time-consuming to reduce the form error completely. Up to date, no report can be found on STS turning with nanometer-level form accuracy.

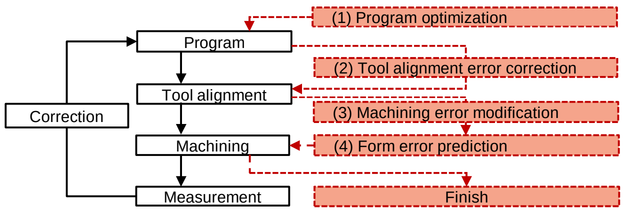
In this work, we proposed a new machining flow which was composed of error correction and prediction based on comprehensive error analysis and simulation. Using the new error correction/prediction system, all the main error factors are optimized and the form error of the finished surface is predicted accurately in advance. Thus, the form error is reduced completely in a single correction-machining cycle, and the form accuracy is improved to the nanometer-level. The effectiveness of the proposed system was verified by experiments.

2. STS turning and error factors

Figure 1(a) shows a schematic diagram of an ultraprecision turning lathe with an STS. In STS turning, freeform surfaces are machined by synchronizing the X-axis and Z-axis movements with the C-axis rotation, as shown in Figure 1(b). A typical machining process consists of three steps: program step for tool path generation, tool alignment step for tool-workpiece alignment, and machining step for surface generation. In STS turning, a number of factors cause workpiece form errors during each step of the process.



(a) STS turning lathe (b) Freeform machining
Figure 1. Schematic diagram of STS turning of freeform surface



(a) Feedback system (b) Correction/prediction system
Figure 2. Diagrams of the proposed machining flow

3. Error correction/prediction system construction

Figure 2(a) shows a conventional machining flow. The form error is corrected by using a feedback correction system in which only a specific error factor is compensated based on the experimentally measured form error. The machining-measurement cycle must be repeated for many times because the form error is decreased gradually in each cycle.

In this study, a new machining flow was proposed, which included error correction and prediction, as shown in Figure 2(b). The flow is composed of four steps: (1) program optimization, (2) tool alignment error correction, (3) machining error modification, and (4) form error prediction. In this machining flow, all the main error factors are optimized in steps (1), (2) and (3) based on error analysis, and the form error of the finished surface is predicted in step (4). All the error corrections are carried out and the finished form error is predicted before machining. In this way, a high form accuracy will be obtained in a single correction-machining cycle.

Comprehensive error analysis and modelling were performed to identify all the main error factors in each step. Numerical simulation was carried out by using MATLAB to clarify the relationship between these error factors and the form error of the finished surface. Based on the simulation results, the error correction/prediction system was constructed. As a simulation test, the form error was predicted for machining of a sinusoidal wave grid, which had a diameter of 1 mm, an amplitude of 50 nm and a wavelength of 100 µm. Comparison was performed for four different cases: without correction, with correction (2), with corrections (1) and (2), with corrections (1), (2) and (3), respectively.

4. Verification by cutting experiment

As a cutting test, a sinusoidal wave grid was machined on a single crystal-silicon wafer by STS turning. In the experiments, an ultraprecision turning lathe Precitech Nanoform X was used. A round-nosed single-crystal diamond tool with a nose radius of 2.0 mm and a rake angle of -30° was used. The feed rate and depth of cut were set to 2 µm/rev and 2.0~2.2 µm, respectively.

5. Results and discussion

5.1. Prediction result by simulation

In the simulation, each machining step had a dominant error factor which had the biggest influence on the form error. Figure 3 shows the simulation results of form errors after each correction step and schematic diagrams of how the form error is caused by the dominant factor. In the program step, the form error is caused by the deviation of tool trajectories, which connect cutting points, from ideal surfaces (Figure 3(a)). The number of the cutting points was a dominant factor. In the correction step (1), the number of cutting points was changed from 13000 to 21000. As a result, the form error was decreased from 8 nmP-V to 1 nmP-V. In the tool alignment step, as shown in Figure 3(b), ΔX and ΔY were the dominant factors, where ΔX and ΔY were the error between the tool tip and the spindle rotation center in X-axis direction and Y-axis direction, respectively. In the correction step (2), ΔX and ΔY were decreased from 3 µm to 250 nm by accurate alignment. As a result, the form error was reduced from 22 nmP-V to 1 nmP-V. In the machining step, the form error is caused by the follow-up error of machine tool, as shown in Figure 3(c). The control parameter of the turning lathe was a dominant factor. In the correction step (3), the control parameter was adjusted according to the machining condition in order to decrease the follow-up error. As a result, the form error was reduced from 13 nmP-V to 5 nmP-V.

Figure 4 shows the simulation results of form errors under different conditions. This figure shows that the form error was reduced in each correction step. The more correction steps were applied, the more form error was decreased. These results demonstrated that all the main error factors were optimized comprehensively by the three correction steps. In the simulation, the form error was predicted to be reduced by 80% with correction steps (1), (2) and (3), compared to the case of machining without any corrections.

5.2. Cutting experimental result

The machined surfaces were measured by a white light interferometer. Figure 5 shows the experimental results of form errors under different conditions, and Figure 6 shows the three-dimensional topography of the surface machined after all the correction steps. Figure 5 shows that the form error was successfully reduced in each correction step. As a result, a sinusoidal wave grid was successfully fabricated with an

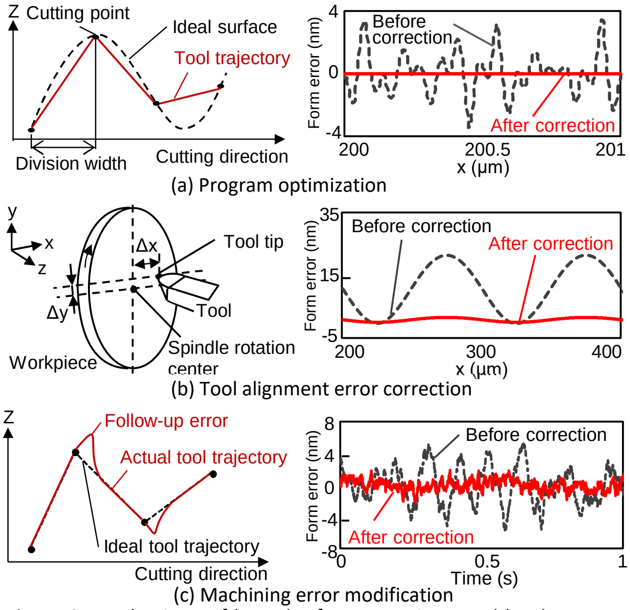


Figure 3. Mechanisms of how the form error is caused by the error factors and simulation results of form errors after each correction step

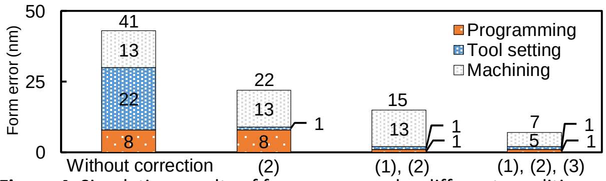


Figure 4. Simulation results of form errors under different conditions

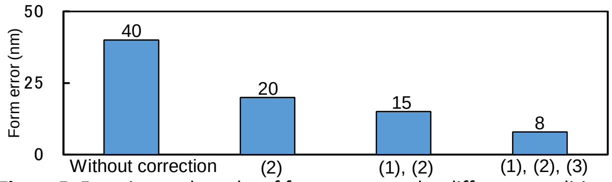


Figure 5. Experimental results of form errors under different conditions

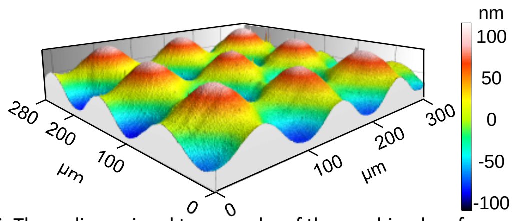


Figure 6. Three dimensional topography of the machined surface

amplitude of ten nanometer-level. A comparison between Figure 4 and Figure 5 shows that the cutting experimental results were in good agreement with the simulation results. It was evident that the proposed machining flow enables to correct all the error factors comprehensively and predict the form error accurately. The form error was reduced by 80% and the form accuracy was improved to 8 nmP-V.

6. Conclusions

A new machining flow composed of error correction and prediction was proposed for STS turning of freeform surfaces, and the constructed error correction/prediction system was applied to the machining of a sinusoidal wave grid on single-crystal silicon. Using the error correction/prediction system, the form error was reduced by 80 % in a single correction-machining cycle, and the form accuracy was improved to 8 nmP-V.

References

[1] S. Scheiding, A.Y. Yi, A. Gebhardt, R. Loose, L. Li, S. Risse, R. Eberhardt, A. Tünnermann, 2011, Proceedings of SPIE 7927 79270N.1-N.11

[2] D. W. K. Neo, A. S. Kumar, M. Rahman, 2014, Precision Engineering 38 49-860