Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-07-0168

Investigation of Segment Turning Process based on Single-amplitude-frequency Criterion for Complicated Multi-Scale Surface Structure

Xiao Lu#, Chi Fai Cheung, Chunjin Wang, Canbin Zhang and Lai Ting Ho
State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China
Corresponding Author / Email: roderic-xiao.lu@connect.polyu.hk, TEL: +852-2766-6576, FAX: +852-2764-7657

KEYWORDS: Multi-Scale Surface Structure, Amplitude-frequency Characteristic, Dynamic Capability, Ultra-precision machining

With the continuously promotion of NC machining technologies, the diamond turning can be adaptively utilized for the manufacturing of multi-scale functional microstructure, which has been increasingly applied in many fields currently. However, the complicated geometrical features due to the multi-scale structure leads to huge challenge for the dynamic capability of machine tool. Specially, focusing on the multi-scale structure, the machining error is dramatically enlarged when cutting along the global-continuous toolpath. In this paper, an investigation is presented for sub-regional toolpath and vacant-path planning in segment turning based on single-amplitude-frequency criterion considering integrated geometrical-physical factors for complicated multi-scale surface structure. Based on the macroscopic analysis from the established kinematic and dynamic model for slow tool servo (STS) turning machine tool, the multivariate mapping relation between microstructure geometry, amplitude-frequency characteristic of axes of machine tool and designed machining trajectory is studied theoretically. The influencing mechanism from amplitude-frequency characteristics to dynamic capability is investigated. Hence, the surface segmentation according to the local amplitude-frequency characteristic of multi-scale structure is carried out and the relating segment turning with multiple feeding processing is planned. Finally, the sub-regional processing is accomplished by STS turning for multi-scale surface structure by stitching toolpath/vacant-path corresponded to the local structure with single amplitude-frequency characteristic so as to adapt to the dynamic capability of machine tool and ameliorate the machining quality, where both the theoretical and experimental investigations have supported the expectation. This method can minimize the influence of the dynamic capability limitation of the machine tool on the machining quality by modifying the toolpath on the basis of the existing machining conditions.

1. Introduction

The multi-scale microstructure has been increasingly applied on various state-of-the-art fields, e.g., optical elements [1, 2], superhydrophobic coatings [3, 4] and bio-surface mimicking [5], etc., where the ultra-precision diamond turning is prone to obtain this kind of structures with high machining quality [6, 7]. However, as the dramatically increased complexity of geometry of multi-scale microstructure, there is a great challenge for the dynamic capability of machine tool to meet the high requirement of machining accuracy and surface finish [8]. As the critical part in ultra-precision manufacturing, the toolpath generation method should be adaptively promoted to the current issues.

Focusing on the microstructure with complicated geometric features, some researchers have proposed their answers to the problems, where the invented segment turning method play a vital role in promotion of the toolpath design in machining process. For instance, Mukaida et al. [9]investigated a tool-servo driven method for segment turning in order to enhance the machining quality of hexagonal micro-lens arrays especially for the edge of the microstructure where the geometric parameters are suddenly changing.Besides, Yeung et al. [10] studied a non-resonant modulation cutting method using segment turning process to design toolpath with vacant path for the micro-dimpled surfaces. Those research studies have practical effectiveness for the complicated microstructural workpiece.However, few of the existing studies have focused on the multi-scale microstructure specially.

Obviously, the multi-scale feature of this kind of microstructure means quite difference than other structures. The adjacent structural elements with different scale are prone to lead to rapid and even sudden change of geometric parameters (e.g., curvature, structural amplitude, etc.), which adversely affects the dynamic performance of machine tool in real-timemachining and finally damage the surface finish. Based on this issue, a creative segment turning method with geometry-dynamic factors analysis as well as the sub-regional machining trajectory design based on Fourier Series is proposed in this paper. The main innovation is to design the sub-regional toolpath with simplified amplitude-frequency characteristics so as to be adaptive to the dynamic capability of the machine tool.

2. Extension of Segment Turning Process Method based on Single-amplitude-frequency Criterion

2.1 Geometric Analysis for Multi-Scale Microstructures by Fourier Series Expansion (FSE)

Compared with the single-scale microstructure, the multi-scale microstructureas shown in Fig.1 dramatically enhance the difficulty of manufacturing for this type of optical components in STS turning, that is, the influence of geometric factor during the processing is strengthened, to illustrate, the geometric parametersthat rapidly change at any point on the surface leads to severe vibration of the machine tool feeding axes as well as thecutting tool during the machining process, which further deteriorates the normal machining trajectory, affect the surface machining profile,cause additional damage to the tool wear and so forth. To sum up, it imposes great challenges to the dynamic capability of the machine tool. Therefore, it is necessary to conduct deep and detailed analysis on the geometric feature of the multi-scale structure. In view of this special structure, an innovative geometric analysis method with better adaptability is proposed in this paper. By evaluating the complex geometric features, the manufacturing difficulty of a certain multi-scale structure is judged by considering the influence of the structuralgeometry on the practical dynamic capability of the machine tool.This is exactly the process of integrating workpiece geometry with the physical factorsduring the machining process in STS turning.

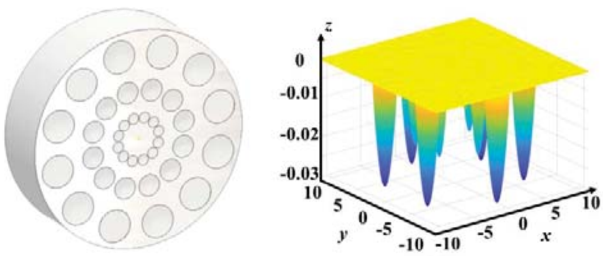

Fig. 1 Typical multi-scale microstructure

2.1.1 Geometry Analysis

When machining the multi-scale microstructure, the C-axis and X-axis of turning machine tool are feeding simultaneously from one cutter contact point (CCP) to the next one to interpolate the sectional profile of complex curved surface in the circumferential direction, meanwhile, the C-axis and Z-axis of machine tool are feeding simultaneously to interpolate the complex curved surface in the axial direction. The construction as well as the kinematic model diagram of machine tool can be seen in Fig. 2. In this investigation, due to the facing operation, how to machine the surface along the axial direction based on the interpolation of C-axis and Z-axis is obviously the key issue which would be focused on in the following sections.Naturally, the facing microstructure isas expansion along the practical spiral toolpath on the C-Z expansion plane so as the geometric feature isresearchedassociated with the motion mode of machine tool, and the final aim of which is to guide the sub-regional toolpath generation in the following sections. To be specific, the profile of multi-scale microstructurealong the pre-generated spiral toolpath is expanded by Fourier series, based on which the complexity of manufacturing in STS turning for the microstructureis evaluated, which can be seen in Fig. 3

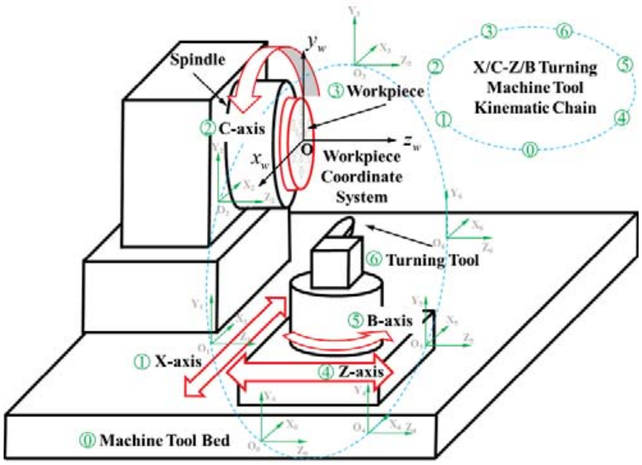

Fig. 2 Construction of machine tool and its kinematic model

On the C-Zexpansion plane, the coordinate value of the $z_w$axison the workpiece coordinate system (WCS) of each point on the profile of multi-scale microstructure along the pre-generated spiral toolpath is set as z which can be same as Z-axis value on the machine coordinate system (MCS) and the polar angle of that can be set as θ. Then, the profile of sectional surface can be expressed as,

$$z = f(\theta) \tag{1}$$

Because the pre-generated spiral toolpath is just utilized to evaluate the surface geometry, the toolpath parameters can be set without the consideration of practical machining, but should be with a certain density to ensure the accuracy of the evaluation.

The functional expression in Eq. (1) is defined as microstructuralexpansion-shape geometric function in this paper.

2.1.1 FSE-geometry Method

FSE is an important mathematic tool which can expand any periodic function as the accumulation of trigonometric function. Hence, the microstructural expansion-shape geometric functioncan be expanded as Fourier series [11]. In this way, the Fourier coefficients and the magnitude-frequency characteristic curve corresponded with the FSE of the profile of multi-scale microstructure along the pre-generated spiral toolpathiscritical foundation for the complexity of manufacturing evaluation and guidance for the sub-regional toolpath generation. This is the key innovation in this research. The practical operation for this process is illustrated in the following sections and its diagram is shown in Fig. 3.

Since the primary motion is the rotational motion of the workpiece, the period of the microstructuralexpansion-shape geometric function can be taken as the period of the rotational motion

2π , and therefore the FSE can be expressed as,

$$z(\theta) = z_0 + \sum_{n=1}^{\infty} z_n \sin(n\theta + \varphi_n) \tag{2}$$

Where, Z_0 is the polar radius of base circle of the profile, Z_n is the magnitude of the *n*th harmonic of the profile for sectional surface and φ_n is the initial phase of the *n*th harmonic of the profile of multi-scale microstructure along the pre-generated spiral toolpath. These Fourier coefficients can be calculated as,

$$\begin{cases} z_0 = \dfrac{1}{2\pi}\displaystyle\int_{-\pi}^{\pi} z(\theta)d\theta \\ z_n = \sqrt{\left(\dfrac{1}{\pi}\displaystyle\int_{-\pi}^{\pi} z(\theta)\cos(n\theta)d\theta\right)^2 + \left(\dfrac{1}{\pi}\displaystyle\int_{-\pi}^{\pi} z(\theta)\sin(n\theta)d\theta\right)^2} \\ \varphi_n = \arcsin\left(\dfrac{\frac{1}{\pi}\int_{-\pi}^{\pi} z(\theta)\cos(n\theta)d\theta}{z_n}\right) \end{cases} \tag{3}$$

Based on the result of FSE, the complexity evaluation coefficient for microstructural geometry would be defined and expressed as,

$$G = \lim_{N\to\infty}\sqrt{\frac{1}{N}\sum_{n=1}^{N}(z_n)^2} \tag{4}$$

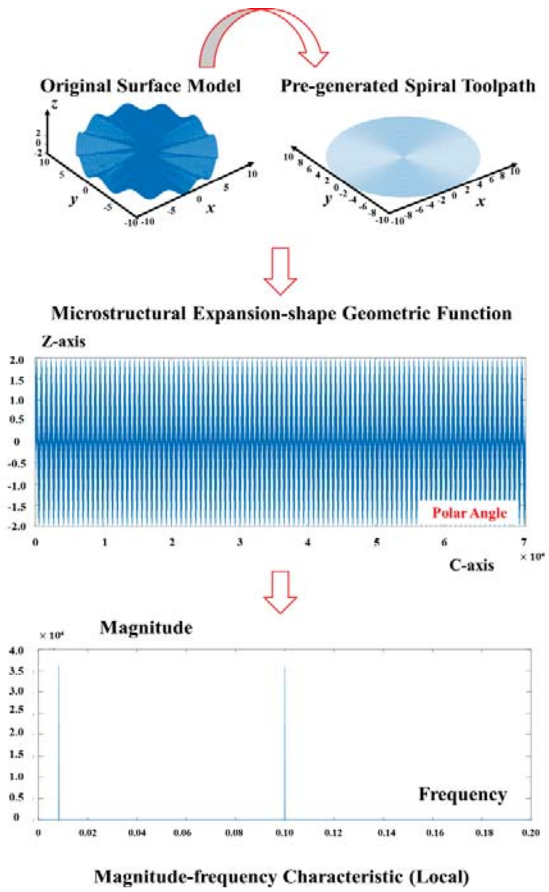

Fig. 3 FSE-geometry Analysis Scheme

In order to the operability of this coefficient in practice, the fitting error of Fourier series should be proposed and set as ε_f . If the *m*th order Fourier series is taken to fit the microstructural expansion-shape geometric function, the fitting error is determined as,

$$\varepsilon_f^m = \sqrt{\frac{\sum_{i=1}^{p}\left(z(\theta_i) - z_0 - \sum_{n=1}^{m} z_n \sin(n\theta_i + \varphi_n)\right)^2}{p-1}} \tag{5}$$

Where, p is the number of sampling points on the profile, and θ_i is the polar angle of the *i*th point.

Given the fitting accuracy of Fourier series as E , when $\varepsilon_f^m \le \mathrm{E}$, this *m*th order Fourier series is certainly taken to fit the microstructural expansion-shape geometric function, and therefore, the complexity evaluation coefficient for microstructural geometry G is determinedas,

$$G = \sqrt{\frac{1}{m}\sum_{n=1}^{m}(z_n)^2} \tag{6}$$

2.2 FSE-dynamic Model to Integrate Geometric and Physical Factors During STS Diamond Turning

Based on the proposed FSE-geometry method, an analysis for kinematic characteristic of Z-axis can be further carried out,that is, the feeding motion of Z-axis when machining along the profile of the cross-section would be also investigated by Fourier series. Therefore, the multivariate mapping relation between microstructural geometry, amplitude-frequency characteristic of axes of machine tool and designed machining trajectory can be found in this section.

From what shown in Section 2.1, the complexity of microstructural geometry will determine the difficulty of manufacturing for such microstructure in STS turning. Thus, the complexity of manufacturing evaluation can be connected to the geometric analysis.

The tool feeding motion trajectory function of Z-axis can be expressed as,

$$Z(t) = z(\omega t) \tag{7}$$

Where, ω is the angular speed of spindle when machining the microstructure, and z is the tool feeding motion trajectory function related to the microstructural expansion-shape geometric function.

Expand this tool feeding motion trajectory function by mth order Fourier series as,

$$Z(t) = Z_0 + \sum_{n=1}^{m} Z_n \sin(n\omega t + \varphi_n) \tag{8}$$

All these Fourier coefficients can be determined as,

$$\begin{cases} Z_0 = \dfrac{\omega}{2\pi}\displaystyle\int_{-\frac{\pi}{\omega}}^{\frac{\pi}{\omega}} Z(\omega t)dt \\ Z_n = \sqrt{\left(\dfrac{\omega}{\pi}\displaystyle\int_{-\frac{\pi}{\omega}}^{\frac{\pi}{\omega}} Z(\omega t)\cos(n\omega t)dt\right)^2 + \left(\dfrac{\omega}{\pi}\displaystyle\int_{-\frac{\pi}{\omega}}^{\frac{\pi}{\omega}} Z(\omega t)\sin(n\omega t)dt\right)^2} \\ \varphi_n = \arcsin\left(\dfrac{\frac{\omega}{\pi}\int_{-\frac{\pi}{\omega}}^{\frac{\pi}{\omega}} Z(\omega t)\cos(n\omega t)dt}{Z_n}\right) \end{cases} \tag{9}$$

The feeding velocity of X-axis v_Z when machining this segment can be determinedas,

$$v_Z(t) = \omega\sum_{n=1}^{m} nZ_n \cos(n\omega t + \varphi_n) < mG \tag{10}$$

As a reult, the analysis forof the kinematic characteristic Z-axis when feeding along the profile of multi-scale microstructure along the pre-generated spiral toolpath is done. With this analysis, the sub-regional toolpath generation considering dynamic capabilityof machine tool based on FSE is realized.

2.3 Sub-regional Toolpath Generation Method Based on Single-Amplitude-Frequency Criterion for Segment Turning

According to the FSE-dynamic model, it can be found that, firstly, the complexity of manufacturing for multi-scale microstructure dramatically increases in STS turning compared with the single-scale microstructure, secondly, if the toolpath is designed in a sub-regional processing method for segment turning where the toolpath for each sub-region of a feeding process is required to meet the capability of single-amplitude-frequency (SAF) as much as possible, the complexity of manufacturing for multi-scale microstructure in practical operation isdecreased so that the machining quality is greatly ameliorated.

Hence, a sub-regional toolpath generation method based on the SAF criterion is investigated in this section.To be specific, firstly, the machining region of multi-scale microstructure is segmented into different sub-regions where the microstructures are in similar scale, secondly, different sub-regions are machined in different feeding process, which means that each time of a certain feeding process, there are sub-region to be practically machined which is defined as machining sub-region and other sub-region(s) without practical machining which are defined as vacant sub-region(s).

Naturally, during each feeding process, the practical toolpath for the machining sub-region and the vacant path for the vacant sub-region(s) should all be well designed in order to guarantee the continuity of STS turning.Besides, the practical toolpath and vacant path are stitched in case of sudden change of tool feeding during the machining process, and the combined practical toolpath and vacant path can be defined as machining trajectory. The sub-regional toolpath (local) in a certain feeding process is shown in Fig. 4 to illustrate this method.

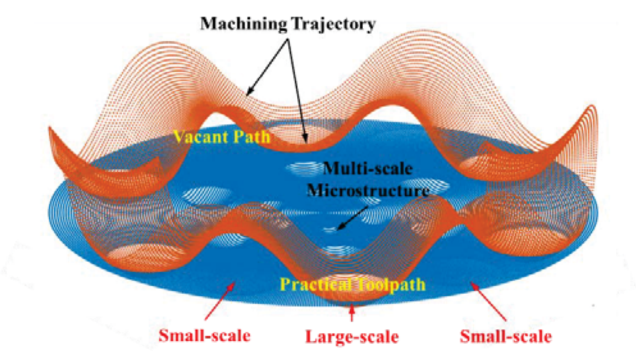

Fig. 4 Sub-regional toolpath

2.4 Experimental Analysis

2.4.1 Simulation

In order to verify the effectiveness of the proposed theoretical model, two experimental simulations arecarried out in this section.

Firstly, the microstructural surface is designed. One is a geometric modelwhere the microstructures are in single scale for a certain group (i.e., the elements of microstructure are in circular pattern), the other one is a geometric model where the microstructures are in multi-scale for a certain group. As shown in Fig. 5(a), for the single-scale microstructure, the diameters of each group are respectively 1 mm, 2 mm, 3 mm (from the center region to the outer boundary), with corresponding maximum depth of 10 μm, 20 μm, 30 μm. As shown in Fig. 5(b), for the multi-scale microstructure, the diameters of each group are respectively 1 mm, 2 mm, 3 mm (from the center region to the outer boundary), with corresponding maximum depth of 10 μm (large-scale, similarly hereinafter) with alternationby 1μm (small-scale, similarly hereinafter), 20 μm with alternation by 2 μm, 30 μm with alternation by 3μm.

According to the proposed FSE-geometry method in Section 2.1, the magnitude-frequency characteristic is analyzed by simulation and the magnitude-frequency characteristic diagram of each model can be seen in Fig. 5(c)-(d). Through the diagrams, it is obviously seen that the magnitude-frequency characteristic of the multi-scale microstructure is more complicated than that of the single-scale microstructure, which can prove the argument of FSE-geometry that the multi-scale microstructure with higher complexity of geometry is related to more orders in FSE and larger complexity evaluation coefficient for microstructural geometry.

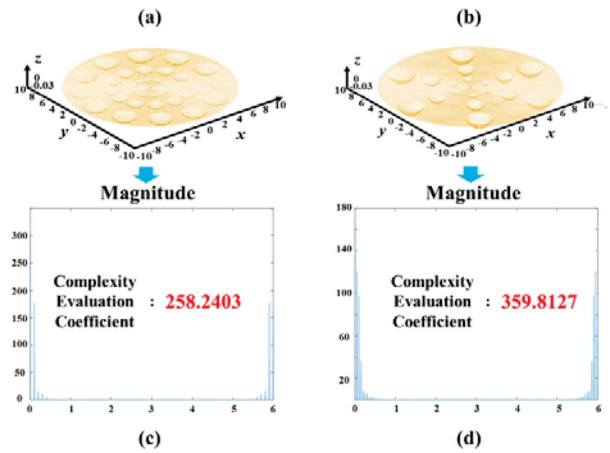

Fig. 5 Simulation for different kind of microstructure: (a)Single-scale, (b) Multi-scale, (c) Single-scale magnitude-frequency characteristic, (d) Multi-scale magnitude-frequency characteristic

Secondly, focusing on the multi-scale structure, the machining trajectory for the control groupis designed by the existing segment turning method, i.e., the toolpath in microstructural element is extended and offset onto the plane region as vacant path, but the machining trajectory is designed to directly connect the large-scale microstructural element and the small-scale microstructural element, which means only one feeding process to manufacture the different scale of microstructure, as shown in Fig. 6(a).On the contrary, the machining trajectory for the experimental group is designed by the proposed method, practically, there are two feeding process with related sub-regional machining trajectory as shown in Fig. 6(b).

According to the FSE-dynamic model, the complexity of manufacturing evaluation is analyzed by simulation. As shown in Fig., the magnitude-frequency characteristic diagram of the machining trajectory based on conventional method is more complicated than that of the two invented sub-regional machining trajectory. Hence, it can be predicted that the machining quality by the proposed method is much better under the certain dynamic capability of a machine tool.

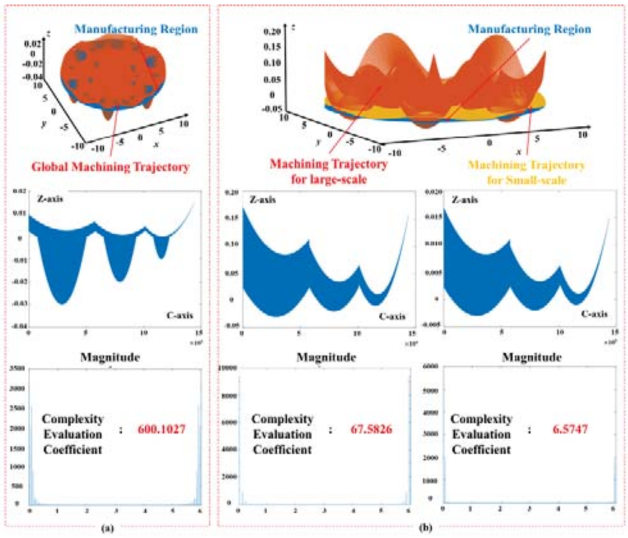

Fig. 6 Machining trajectory/toolpath generation and FSE-dynamic analysis: (a) Conventional segment turning, (b) Proposed segment turning

2.4.1 Practical Cutting Experiment

In order to verify the effectiveness of the proposed sub-regional toolpath generation method based on single-amplitude-frequency criterion for segment turning, a cutting experiment is carried out in this section on the machine tool Nanotech 450 as shown in Fig. 7, using the machining trajectory designed in Section 2.4.1. The cutting toolis selected with nose radius of 0.5 mm and clearance angle of 15°, the toolpath parameters are set as spiral spacing distance of 0.005 mm and iso-polar-angle value between adjacent CCP of 0.5°, and the spindle speed value is maintained at 83 r/min during the machining process.

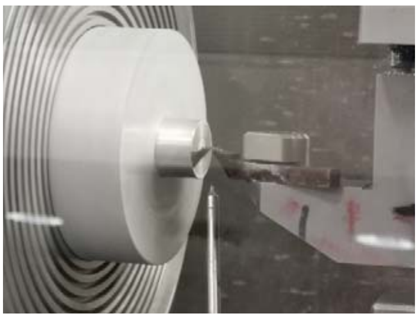

Fig. 7 Machining Process

After manufacturing in STS turning, the two workpieces shown in Fig. 8 are observed by the microscope for the detailed shape of machined microstructure. It can be seen in Fig. 8(a) that the microstructure obtained by the conventional method has significant vibration rippling which is perpendicular to the toolpathas well as the machined mark which is parallel in the microstructural element (3mm), and severe profile error ofboundary shape for the machined region. By contrast, as shown in Fig. 8(b), the microstructure obtained by the proposed method has significant amelioration on the surface finish quality as well as the profile accuracy.

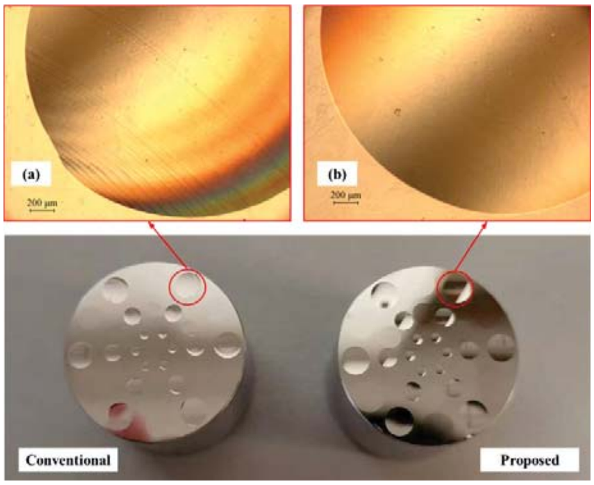

Fig. 8 Surface microstructural finish observation

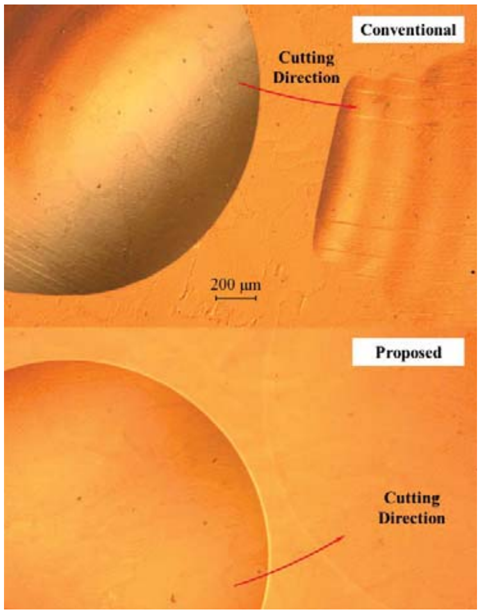

Fig. 9 Multi-microstructural finish observation

In addition, Fig. 9 shows that when cutting tool machining from the large-scale element (2mm) to the small-scale element (2mm), the vibration rippling (perpendicular to the toolpath) is much more severe in the workpiece of conventional method. However, by the promotion of sub-regional toolpath generation method based on single-amplitude-frequency criterion for segment turning, the problem of vibration rippling between multi-scale microstructural elements is obviously solved, and the machining quality including surface finish and profile accuracy has been exactly ensured, which can successfully prove the effectiveness of the proposed method.

3. Conclusions

In this paper, an innovative sub-regional processing method for segment turning based on SAF criterion has been investigated. The key issue is using FSE to connect the geometric factors of workpiece and the machining physical factors of machine tool. Therefore, the sub-regional machining trajectory can be better adaptive to the dynamic capability of machine tool and specially lead to amelioration of machining quality for the multi-scale microstructure.

By the simulations, the effectiveness of the proposed FSE-geometry analysis method as well as the FSE-dynamic model has been proved. Furthermore, the cutting experimental results shows that the proposed method can significantly enhance the machining quality in practice. On the contrary, although the conventional segment turning method has promotion for the manufacturing at microstructural edge, the global machining problems are still hardly to be solved, especially as the severe vibration rippling. To be specific, due to the limitation of the dynamic capability of the machine tool, when the cutting tool feeds along the machining trajectory from the large-scale element to the small-scale element, the following error of Z-axis is dramatically deteriorated as the complicated geometric feature of multi-scale microstructure, that is, the cutting tool cannot precisely feed along the designed machining trajectory, what's worse, severe vibration occurs there, which lead to damage to the profile manufacturing of the microstructural element and naturally, there is extremely low machining quality.

In addition, the following error (FE) measured by machine tool system in real time can also support the perspectives above. As collected in Table 1, the maximum FE of Z-axis when machining workpiece by the conventional method can reach to 2.440 μm, considering that the maximum scale of the microstructure is 30 μm, the effect of FE here for the machining quality cannot be ignored. By contrast, the maximum FE of Z-axis when machining workpiece using the proposed method has been decreased by 56.27%, which means the optimized machining quality under existing machining conditions.Of course, due to the multiple feeding process design, the machining time of the proposed method is also extended to be doubled. However, thefirstly-considered issue in ultra-precision diamond machining is still the machining quality rather than machining efficiency, thus, the proposed method can still be evaluated as optimization.

Table 1 Comparison of real-time machining physical parameters

Workpiece	Z-axis Maximum FE	Machining Time
Conventional	2.440 μm	1446 s
Proposed	1.067 μm	2892 s

The proposed method in this paper provides critical guidance to the segment turning technology and support the corresponding theoretical explores in the field of microstructure ultra-precision machining. However, in this paper,the dynamic analysis by FSE is not precise and deep enough, and the guidance for machining trajectory design is just directional. Thus, promoted physical model that is more applicative and accurate is needed to establish and further related research will be carried out.

ACKNOWLEDGEMENT

The authors would also like to express their sincere thanks to the Research Committee of The Hong Kong Polytechnic University for their financial support of the project through a PhD studentship (project code: RHM7). The authors would also like to express their sincerely thanks to the financial support from the Research and Innovation Office of The Hong Kong Polytechnic University (Project code: BBX2 and BBX7)

REFERENCES

1. Kang H.S., Lee S.W. and Park J.K., "Monolithic, Hierarchical Surface Reliefs by Holographic Photofluidization of Azopolymer Arrays: Direct Visualization of Polymeric Flows", Adv. Funct. Mater., Vol. 21, pp. 4412-4422, 2011.
2. Liu M.Y., Cheung C.F., Feng X.B., Wang C.J., "Diamond Machining of Freeform-Patterned Surfaces on Precision Rollers", J. Adv. Manuf. Technol., Vol. 103, pp. 4423–4431, 2019.
3. Lei Y.L., Wang Q.R. and Huo J.C., "Fabrication of Durable Superhydrophobic Coatings with Hierarchical Structure on Inorganic Radome Materials", Ceram. Int., Vol. 40, pp. 10907-10914, 2014.
4. Bhushan B., Jung Y.C. and Koch K., "Micro-, Nano- and Hierarchical Structures for Superhydrophobicity, Self-Cleaning and Low Ashension", Philos. trans., Math. phys. eng. sci., Vol. 367, pp. 1631-1672, 2009.
5. To S., Zhu Z.W. and Zeng W.H., "Novel End-fly-cutting-servo System for Deterministic Generation of Hierarchical Micro-Nanostructures", CIRP Ann., Vol. 64, pp. 133-136, 2015.
6. Hilpert E., Hartung J., Risse S., Eberhardt R. and Tünnermann A., "Precision Manufacturing of aLightweight Mirror Body Made by Selective Laser Melting", Precis. Eng. Vol. 53, pp. 310-317, 2018.
7. Yuan W., Cheung C.F., "Theoretical and Experimental Investigation of Tool Indentation Effect in Ultra-Precision Tool Servo-Based Diamond Cutting of Optical Microstructured Surfaces", Opt. Express, Vol. 29, pp. 39284-39303, 2021.
8. Ma J.W., Lu X., Jia Z.Y., Li G.L., Ye T. and Liu W., "Subregional Process Method with Variable Parameters Based on A Potential Field in Slow Tool Servo Machining for A Complex Curved Surface", J. Manuf. Sci. Eng., Vol. 144, No. 4, pp. 041006-041021, 2022.
9. Mukaida M. and Yan J.W., "Fabrication of Hexagonal Microlens Arrays on Single-Crystal Silicon Using the Tool-Servo Driven Segment Turning Method," Micromachines, Vol. 8, No. 11, pp. 323, 2017.
10. Yeung C.S., Yang Y., Du H.H., Wang J.J. and Guo P., "Friction Reduction Performance of Microstructured Surfaces Generated by Nonresonant Modulation Cutting", Proc. Inst. Mech. Eng., Part C, Vol. 233, No. 12, pp. 4120-4127, 2019.
11. Deng Z.L. and Wang X.K., "Analyses on Feed Kinematic Behaviors in Turning of Noncircular Sectional Element Based on Fourier Series", Chin. J. Mech. Eng-En., Vol. 2, pp. 10-14, 1999.