Fast-tool-servo micro-grooving freeform surfaces with embedded metrology

Zhen Tong^a, Wenbin Zhong^a, Suet To (2)^{b*}, Wenhan Zeng^a

^a EPSRC Future Metrology Hub, Centre for Precision Technologies, University of Huddersfield, Huddersfield, HD1 3DH, UK

^b State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong Special Administrative Region, China

To improve machining capability of diamond turning of hierarchical structured surfaces, fast-tool-servo (FTS) turning using a sharp point diamond cutting tool (tool tip width $<30\text{ }\mu\text{m}$) is proposed to generate micro grooves on freeform surfaces. An embedded measurement probe is employed to improve the tool alignment accuracy and also to realise on-machine surface measurement (OMSM) of FTS machined surfaces before surface micro-grooving. A self-developed controller board is used to collect and synchronise all signals between the machine tool, FTS controller and measurement system. The feasibility of the proposed method is demonstrated through successfully generating micro grooves on freeform lens array and an Alvarez lens.

Cutting, surface, diamond tool

1. Introduction

Local modification of surface with micro/nano-texture (arrays of geometric, non-geometric, nature-inspired patterns) provides an effective way to change surface properties in the desired area without altering the properties of bulk material. Owing to the promising and vast applications of freeform and functional structured surfaces in optics and electronics, solar energy, cell biology, bioengineering and medical science, a variety of micro/nano-machining techniques, for example, single point diamond turning (SPDT), micro milling, ultra-precision grinding, fast-tool-servo (FTS), fly-cutting and ultrasonic assisted machining, have been continuously developed in recent years to meet the increasing requirements on both accuracy and complexity of micro/nano-structured surfaces [1]. However, due to the inherent limitations such as machining errors induced by cutting tool wear and motion errors of machine tools, the scale-up fabrication of structured surfaces of sub-micro or tens of nanometres form deviation remains challenging, especially for surface grooves/step/patches of large high-aspect ratio.

In recent years, micro/nano-machining using facet, sharp point (S-point) and structured cutting tools provides an alternative way to generate surface structures/patterns [2-4]. With the advance of FIB/Laser-assisted shaping of cutting tools, custom designed micro/nano-structures can be generated on cutting tool tips and grinding wheels. The structures pre-fabricated on tools can be replicated on material surfaces through cutting. Periodic and non-periodic structures/patterns were reported to be successfully generated through ultra-precision lathe turning (for soft metals) [4] and grinding (for HSS) [5]. However, the iterative process of diamond machining and surface measurement brings extreme challenges when using facet/S-point diamond cutting tools for surface structuring on freeform

surfaces, especially the issues associated with toolpath planning, tool-workpiece alignment between process steps, and robust surface characterisation method. Most recently, the integration of measurement sensors into ultra-precision machine tools provides a promising solution to achieve on-machine surface measurement (OMSM) in ultra-precision freeform machining [6-8]. Through systematic machine tool motion error identification and calibration [8], an error map generated from embedded optical measurement results allows corrective machining to be carried out to correct identified machining errors without remove the sample from machine. It provides new possibilities to improve the machining efficiency and reliability of diamond turning.

This paper systematically reports the new research progress of surface structuring on freeform using a S-point diamond cutting tool with the assistance of developed OMSM system. The focuses are on the system integration and data synchronisation of FTS with measurement probes and the demonstration of the micro/nano-manufacturing capability of the proposed system-integrated machining technique. A data format conversion method is developed to allow the on-machine surface characterisation, i.e. surface association, filtration and feature characterisation. The results indicate that owing to the unprecedented merits of OMSM, this technique has led to the hope for breaking the technical bottleneck for closed-loop manufacturing and measurement of advanced freeform surfaces.

2. System integration of FTS with measurement probe

2.1. System integration

The experimental platform consists of an ultra-precision diamond turning machine (Nanoform250, Precitech), an FTS system (FTS-400, Kinetic Ceramics, with a maximum stroke of

400 μm @ movement frequency of 100 Hz), and a confocal probing system with reproducibility less than 9 nm (CHRocodile S Precitec, theoretical resolution of 0.01 nm, measurement range of 100 μm , maximum sampling rate of 2 kHz).

As shown in Fig. 1, the integration of measurement sensors into ultra-precision machine tool requires stringent real-time data synchronization between surface measurement sensors, FTS controller and machine tool Computer Numerical Control (CNC) system. The incompatibility of the control interface (in both hardware and software) between the three systems has hindered the data synchronization. To solve this problem, a dedicated secondary controller (HudCNC) was in-house developed to synchronise and control all integrated systems with the CNC system. The HudCNC was used to collect and synchronise all signals and data between machine tool, fast tool servo controller and measurement system to achieve closed-loop freeform manufacturing and metrology. The controller reads cutting tool position from axes encoders in real-time and implements surface interpolation and compensation algorithms to calculate the instant tool position from the point cloud of designed surface geometry. The measurement sensor is synchronised with tool position with trigger signals from HudCNC to control OMSM process. The HudCNC communicates with an independent PC equipped with high-performance CPU to store and manage the data flow and signal processing (sampling, data registration, and surface characterisation).

Fig. 1. System integration of FTS, OMSM system with machine tool.

2.2. User interface control panel design

A user-friendly interface (UI) was designed with functional operations buttons (e.g. sampling rate, active probe, data synchronisation operations, etc.) and a data visualization window was designed to show real-time monitored surface measurement results (Fig. 2). The 2D profile of machined surface can be created immediately with the uploaded data from HudCNC. This functional module is very useful for fast on-machine inspection of machined surfaces. It offers fast tool alignment and processing parameters optimisation without remove samples from machine.

3. FTS micro-grooving on freeform surfaces

The integration of OMSM system into ultra-precision FTS freeform machining environment realise the closed-loop of freeform manufacturing and surface measurement. To extend the FTS machining capability to hierarchical structured surfaces, FTS turning using a S-point cutting tool is proposed to generate

micro grooves on pre-FTS machined freeform surfaces. Two typical freeform surfaces, 4×4 lens array (Fig. 3(a)) and Alvarez lens (Fig. 3(c)), lens coefficient of $2.1213\text{e-}4$, were selected as to demonstrate the feasibility the proposed machining method.

3.1. Cutting toolpath planning

A feature-based freeform cutting toolpath generation system with a tool radius compensation function was developed. After surface geometrical design (Figs. 3(a) and (c)), the whole surface was sampled with high density point cloud with user defined angular and radial resolutions. The developed controller can process up to 5 million points so the point cloud is precise enough for the proposed surface. In machining, the actual cutting tool path is in a shape of spiral (Figs. 3(b) and (d)). Unlike slow-tool-servo process where a cutting tool is following a designed tool motion trajectory controlled by machine CNC in real-time, for the FTS machining, the HudCNC interpolates the designed point cloud at a fix rate of 2 kHz to generate actual cutting toolpath. The toolpath spacing increases with applied feedrate and spindle speed. Thus, there is a trade-off between the smoothness of toolpath and machining efficiency.

Fig. 2. UI control panel with different functional modules

Fig. 3. Cutting toolpath generation: (a) designed lens array; (b) cutting tool trajectories of lens array; (c) designed Alvarez lens; (d) cutting tool trajectories of Alvarez lens. (Note: the spacing of cutting toolpath has been reduced for clarity purpose)

3.2. Tool alignment with embedded probe

The tool alignment error consists of the deviations between tool tip and spindle centre in X and Y directions. With assistance the of the OMSM system, a two-step tool alignment method is proposed for both freeform machining using normal FTS cutting tool and the micro-grooving with S-point tool. In the first step, a tool was positioned slightly under the spindle centre. Through

diamond face turning, it will form a cylinder uncut area in the workpiece centre. The tool height compensation value (Y direction) can be calculated as a half of the on-machine measured maximum diameter of the uncut area. After the height alignment, 2nd flat cutting (plunge cutting for S-point tool) was performed with the cutting tool short of spindle centre. The tool X direction compensation value is the radius of OMSM measured uncut area. Less than 1 μm alignment accuracy was achieved in this study.

3.3. Machining with S-point cutting tool

Fig. 4 shows the experimental setup of the integrated FTS machining with OMSM probe mounted besides tool holder. A motorised Y stage ($<0.1 \mu\text{m}$ motion accuracy) and two miniature linear stages ($0.1 \mu\text{m}$ motion accuracy) were mount on the machine tool Z-axis for adjustment of tool height and probe position respectively. Before micro-grooving with S-point cutting tool (tool tip width $<30 \mu\text{m}$), two designed freeform surfaces were machined using a normal FTS diamond cutting tool (tool radius of 0.3 mm). A measured surface with roughness $S_q < 50 \text{ nm}$ was achieved under spindle speed of 240 rpm and feedrate of $5 \mu\text{m/rev}$. After each cutting path, the machined surface was scanned by integrated measurement probe. The sampling rate is set at 2 kHz under spindle speed of 120 rpm and feedrate of $5 \mu\text{m/rev}$. It takes about 15 minutes for scanning the whole surface.

Fig. 4. Experimental setup and machined freeform surfaces in Brass: (a) lens array and (b) Alvarez lens.

4. OMSM results and discussion

4.1. OMSM data format conversion

The OMSM data is stored in cylindrical coordinate after the fast-spiral scanning. However current surface characterisation software and standards are specialised in lattice grid data format that normally collected through raster scanning path. To ensure the developed OMSM is extensible and compatible to current ISO standards [9,11], a data conversion algorithm was developed to compile the data into surface data file (SDF) format (Fig. 5).

Fig. 5. Data format conversion from spiral to lattice grid data, SDF format (Points A-D represent points collected in spiral scanning and P represent a point in SDF file).

As schematically shown in Fig. 5, the data conversion includes three steps: (i) Delaunay triangulation was performed on OMSM data points in the XY plane; (ii) the triangle that encloses a given raster scanning point P was identified; and (iii) linear

extrapolation was performed within the triangle to determine the Z value of the point. After the data format transition, all data measured by on-machine probes can now be fast processed by existing analysis software such as Mountainsmap and Surfstand.

4.2. Data analysis and surface characterisation

To characterise the machined micro grooves on freeform surfaces, a set of tools for freeform structured surface association, filtration and feature characterisation were proposed and applied for data processing, including an adaptive nonlinear PDE filtration [9], high order robust Gaussian regression filter for form-removal (F-operator) [10] and a pattern-analysis based segmentation method for feature characterisation [11].

Fig. 6 shows a set of results by using the proposed flow of surface characterisation. Through the nonlinear PDE filtration, the tool marks left on plane surface were successfully removed while keeping the important surface geometrical features in each lens (Fig. 6(b)). The geometrical information of each individual lens can then be exacted by using the 2nd order robust Gaussian regression filter as evident in Fig. 6(c)). Fig. 6(d) shows the result of pattern analysis. The whole lenses array was segmented into individual lens and the dimension of each individual lens, lenses distribution and the deviation of the lens array can be characterised by using this pattern-analysis based segmentation method. The mean value of the minimum Z value of lenses is $19.662 \mu\text{m}$ which is 338 nm short of designed specifications, indicating that a form accuracy less than 350 nm was achieved.

Fig. 6. Surface characterisation of lens array (a) OMSM raw data, (b) after tool mark removal, (c) geometry of one lens, and (d) segmentation analysis result. (Note: the highlighted red and green areas in Fig.6(d) are recognised defects by using the proposed pattern analysis method.)

Using the same toolset, micro grooves generated on each lens can be exacted and analysed as shown in Fig. 7. The nonlinear PDE filtration and 2nd order robust Gaussian regression filter can filter out the lens geometry and keep only the feature of micro grooves. Fig. 7(c) is the extracted micro grooves after lens shape and measurement outlier removal. This data can then be further used for surface parameters and area parameters analysis in order to get more detailed features of machine micro grooves, for example, the cross-sectional profile of machined micro grooves (Fig. 7(d)). The slightly non-uniformity of micro-groove depth ($< 80 \text{ nm}$) might result from the mis-alignment of workpiece and S-point diamond tool. The FTS tool servo motion error, tool wear also attributes to this non-uniformity.

Fig. 8 demonstrated another example of Alvarez lens with defined freeform geometry and machined micro grooves on it.

Fig. 8(a) is the on-machine surface measured raw data. Fig. 8(b) is the extracted micro grooves by using Robust Regression filter while Fig. 8(c) is the result showing the micro grooves with measured outliers filtered out. Fig. 8(d) shows a small cross-sectional profile of Fig. 8(c), from which the geometry accuracy of the machined micro grooves can be evaluated.

Fig. 7. Surface characterisation of machined 4×4 lens array with micro grooves: (a) overview of lens array with micro grooves, (b) a single lens with micro grooves, (c) extracted micro grooves after lens shape and measurement outlier removal, (d) cross-sectional view micro grooves.

Fig. 8. Surface characterisation of Alvarez lens with micro grooves: (a) OMSM measured raw data, (b) after 2nd order robust regression filter, lens shape removed, (c) optical measurement outlier removal by thresholding operation, (d) cross-sectional view of micro grooves.

The synchronization of OMSM with FTS machining closes the loop of ultra-precision freeform manufacturing and surface metrology. It significantly improves the machining efficiency by reducing the time for surface measurement and the repeated operations on tool-workpiece alignment. The surface form information measured after FTS provides real-time information of machined surface which allow fast S-point tool alignment operation and accurate toolpath planning for the followed micro-grooving process. The OMSM and surface characterization allow robust on-line inspection and quality control of machined structured surfaces. The measuring value, linearity error and pitch error have been considered to estimate the overall measurement accuracy. The calibration of confocal sensor was done in factory showing that a reproducibility of < 9 nm has been achieved. The fast and robust data processing algorithms that employed for surface characterisation have been comprehensively tested through SoftGauges developed by national/international labs, such as NIST, NPL, etc. Data analysis was done in-line and the time cost depends on the data density and selected operations. Typically, the developed 2nd order robust Gaussian regression filter will take less than 1

second for a 1024×1024 data processing and the pattern analysis will take about 5 seconds. So, the overall time for those analysis is < 6 seconds. Corrective machining based on the error mapping can then be carried out to improve the machined surface quality if necessary [8]. The proposed method is generic and can be adjusted and applied to most popular ultra-precision machining tools (Moore Nanotech, Ametek Precitech).

5. Conclusions

A system integrated FTS machining and measurement platform has been developed to generate micro grooves on freeform surfaces. Hardware integration, data processing flow and GUI system have been developed and reported. The novelty of this research resides in the development of a cost-effective technical solution to synchronise and control all integrated sensor systems with machine CNC system to achieve closed-loop process control of freeform manufacturing and metrology. It provides a systematic solution to improve the automation level of ultra-precision freeform machining in terms of improved tool alignment accuracy (<1μm), fast data synchronisation and transition, and integrated OMSM and surface characterisation function. The feasibility of the proposed method has been demonstrated through successfully generating microstructures in freeform lens array and an Alvarez lens. The non-stop manner of the developed system will allow more complex freeform surfaces to be designed and tested through high machining accuracy, optimal machining parameters, short lead time, and low-cost.

Acknowledgements

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of Future Metrology Hub (Ref: EP/P006930/1), the European Union's Horizon 2020 research and innovation programme under grant agreement No. 767589, the Research Grants Council of the Hong Kong Special Administrative Region (PolyU152021/17E) and National Natural Science Foundation of China (51675455).

References

- [1] Fang F, Zhang X, Weckenmann A, Zhang G, Evans C (2013) Manufacturing and measurement of freeform optics. *CIRP Annals* 62(2): 823-846.
- [2] Zhu Z, Tong Z, To S, Jiang X (2019) Tuned diamond turning of micro-structured surfaces on brittle materials for the improvement of machining efficiency. *CIRP Annals* 68(1): 559-562.
- [3] Brinksmeier E, Preuss W (2012) Micro-machining. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370(1973): 3973-3992
- [4] Luo X, Tong Z, Liang Y (2014) Investigation of the shape transferability of nanoscale multi-tip diamond tools in the diamond turning of nanostructures. *Applied Surface Science* 321:495-502.
- [5] Stepien P (2011) Deterministic and stochastic components of regular surface texture generated by a special grinding process. *Wear* 271: 514-518.
- [6] Gao W et al., (2019) On-machine and in-process surface metrology for precision manufacturing. *CIRP Annals* 68(2): 843-866.
- [7] Zou X, Zhao X, Li G, Li Z, Sun T (2017) Non-contact on-machine measurement using a chromatic confocal probe for an ultra-precision turning machine. *Int. J. Adv. Manuf. Technol.* 90(5-8): 2163-2172.
- [8] Li D, Tong Z, Jiang X, Blunt L (2018) Calibration of an interferometric on-machine probing system on an ultra-precision turning machine. *Measurement* 118: 96-104.
- [9] ISO 16610-71:2014 Geometrical product specifications (GPS)-Filtration-Part 71: Robust areal filters: Gaussian regression filters
- [10] Zeng W, Jiang X, Scott P (2010) Fast algorithm of the Robust Gaussian Regression Filter for Areal Surface Analysis. *Measurement Science and Technology* 21(5): 055108.
- [11] ISO 16610-85:2013 Geometrical product specifications (GPS)-Filtration-Part 85: Morphological areal filters: Segmentation