Surface Topography: Metrology and Properties

PAPER

A closed-loop feature-based FTS patterning and characterisation of functional structured surfaces

Zhen Tong, Wenhan Zeng, Wenbin Zhong and Xiangqian Jiang
E-mail: z.tong@hud.ac.uk

Abstract

To improve the feasibility and efficiency of ultra-precision surface structuring, a closed-loop fast-tool-servo (FTS) surface patterning and measurement system is developed with functional modules of feature-based tool path generation, embedded surface measurement and integrated surface characterisation toolkit. A dedicate controller HUDCNC is developed for the process control of FTS surface patterning and on-machine surface measurement (OMSM). Algorithms are developed for data formatting and transformation of designed patterns into the FTS cutting points (maximum number of 5 million points). The feasibility and performance of the proposed closed-loop FTS machining system are demonstrated by successfully generating typical functional structured surfaces including periodic structures, patterns and tessellations, biological surfaces, profile and character combinations. The results indicate that the feature-based FTS patterning and surface characterisation system provides a promising solution to the design and manufacturing of high-precision functional structured surfaces. The integrated OMSM system and the surface characterisation toolkit allow the fast inspection and quality control of the machined functional surfaces.

1. Introduction

Owing to the wide applications of functional micro/nano-structured surfaces, fundamental research into the machining and surface functionalities has received significant global research efforts and been fruitful for the past 20 years. Many elegant studies have highlighted the benefits of bio-inspired functional surfaces because of a variety of naturally functional responses include superhydrophobicity, self-cleaning, dry adhesion, reduced drag, reduced wear/contact friction, anti-fouling, and optical properties (specific structural colours/anti-reflective behaviour) [1, 2]. Various mechanical, physical and chemical based methods have been continuously developed to meet the increasing requirements on both form accuracy and surface finish. Most recently, the available manufacturing processes such as diamond machining, micro milling, vibration-assisted texturing, abrasive machining, physical-beam-assisted machining, electrical/chemical-based machining etc and their capabilities to generate multiscale/hierarchical structured surfaces have been reviewed in a keynote by Brinksmeier et al in 2020 [3].

Among those technologies, ultra-precision fast-tool-servo (FTS) diamond machining and its variations (nano-fast-tool-servo (nFTS), virtual-spindle-tool-servo (VSTS) allow the deterministic generation of a wide range of surface structures enabling advanced optics and micro-components applied in energy, medical device and illumination system etc [4, 5].

The earliest work on FTS machining can be dated back to 1985. Patterson et al [6] at the Lawrence Livermore National Laboratory designed a linear actuator driven FTS system in the Large Optics Diamond Turning Machine (LODTM). Later on, Manfred at the Fraunhofer Institute for Production Technology (IPT) designed the first hybrid FTS system that included a piezoelectric actuator with a linear motor [7]. Since then there are continuous efforts to improve FTS machining capability, i.e. the amplitude of stroke and frequency. Typical examples are an electromagnetically driven ultra-fast tool servo system [8] with the stroke of 30 μm and the bandwidth of 23 kHz and two nano-FTSs [9] featuring strokes of 500 nm and 350 nm at frequencies up to 5 kHz and 10 kHz respectively. A dual-axial fast tool servo system [10]
has also been developed to adaptively control the depth of cut in feed direction to achieve high-efficient ductile machining of brittle materials. Most recently, with the advancement of embedded surface metrology, there are pioneering works reporting the feasibility of integrating embedded surface measurement systems into ultra-precision machining environment [11–13] to close the loop of ultra-precision tool-servo-based machining and surface measurement.

With respects to those achievements, there are three major challenges in FTS machining of functional micro/nano-structured surfaces: (1) the scalability of FTS machining against the minimum tool-tip geometries and wear resistance of single crystal diamond cutting tools; (2) the mathematical expression of complex structured surfaces for cutting tool path generation; (3) the surface measurement and feature characterisation for FTS process diagnosis and optimisation. For instance, the complexity of a machined structured surface and the smallest machinable structure size mainly depend on the sharpness and geometries of the applied cutting tool and the positioning accuracy and flexibility of how the cutting tool can be controlled and aligned during the FTS machining process. Examples have also been discussed and highlighted in [1] that there are no clear correlations between Ra-parameter and the drag reduction function of snake skins, because the 2D Ra-parameter calculated from lines of a white light interferometry (WLI) measurement would miss and almost certainly will not contain the useful topography information associated with the surface drag reduction. To ensure high product quality and good behaviour under functional constraints, the characterisation of micro-dimensions, geometry and surface features has become a very important subject in surface metrology. In 1990s, stable segmentations and associated feature parameters have been developed and subsequently adopted by ISO 16610-85 [14], ISO 16610-45 [15], and ISO 25178-2 [16]. Most recently, a framework to characterise the functional freeform and micro/nanostructured surfaces was proposed in a book of Jiang & Scott [17] with examples to show how feature-based surface characterisation method can be applied to any scalar field and to any topology: profile, areal, freeform surfaces (true three dimensional surfaces, both closed and open) etc. How to accurately generate and characterise surface features in a cost-effective manner has significantly limited the further exploration of advanced surface functionalities.

In this paper, a closed-loop FTS surface patterning and measurement system was developed with functional modules of feature-based tool path generation, embedded surface measurement, and integrated surface characterisation toolkit. A variety of feature-based surface characterisation methods were employed into the closed-loop FTS process chain to evaluate the machined structured surfaces. Through controlled ultra-precision FTS surface structuring, the testing features designed to improve/alter the surface physio-chemical properties can be generated. The feasibility and performance of proposed closed-loop FTS machining system are demonstrated by successfully generating of typical functional structured surfaces with results indicating that, the proposed feature-based FTS machining and surface characterisation provide a promising solution to improve the flexibility and efficiency of FTS-based surface structuring/patterning.

2. Closed-loop FTS patterning and measurement

The integration of on-machine surface measurement (OMSM) system into ultra-precision machining environment is regarded as the key enabling technology to further improve the accuracy and efficiency of ultra-precision machining [18–20]. In our previous study, two different measurement systems (a dispersed reference interferometer [13] and a chromatic confocal probe [11]) have been successfully integrated into an ultra-precision diamond turning machine (Nanoform 250, Precitech) to close the loop of tool-servo-based machining and surface measurement. In this study, the chromatic confocal probe is selected because of its large aperture and high resolution in surface measurement of structured surfaces. The focus of this work is on the development of a feature-based tool path generation for functional structured surfaces and how to integrate feature-based surface characterisation as a toolkit into the whole process chain for in-line quality assessment.

2.1. System integration

The overall FTS machining and measurement platform consists of an ultra-precision diamond turning machine (Nanoform 250, Precitech), an FTS system (FTS-400, Kinetic Ceramics), and a confocal probe measurement system. The FTS system has a maximum stroke of 400 μm at the 100 Hz moving frequency (maximum 800 Hz). The chromatic confocal optical probe is preferred for non-contact surface measurement owning to its compact size (fibre connected probing technology of large aperture), high noise immunity, and high measurement rate. The calibrated specifications of the sensor are listed in table 1.

To solve the problems of data processing and synchronisation raised by the incompatibility of interface between the FTS system, machine tool and the confocal measurement sensor, a dedicated controller (HUDCNC) was self-developed to regulate the data flow between those systems, as illustrated in figure 1. During FTS machining, the machine tool motions are controlled by its own closed-loop control system (UPx) with the feedback from embedded encoders (picometer resolution). The HUDCNC reads and compile encoders’ signal to track the change of tool
position in real-time and generates instant FTS value through the interpolation of designed surface point data set. The FTS tool head movement was triggered by a voltage generated from HUDCNC. In order to guarantee the control resolution, an 18-bit high-precision digital to analog converter (DAC) was selected and used in HUDCNC. The calculated scaling error is less than 1.52 nm.

To realise on-machine measurement, the HUDCNC tracked machine axes positions in real-time and triggered the probe for surface measurement under a measurement rate of 2 kHz. The measurement data was synchronized with the instant positions of the probe. After the scanning, a three-step data conversion algorithm was adapted to convert the OMSM data set to standard surface data file (SDF) format for more detailed topography analysis [11]. A systematic machine tool motion error measurement and probe calibration methods were applied to improve the confidence of OMSM results [21].

2.2. Feature-based FTS tool path generation

The mathmatic expression of a functional surface is required to generate cutting tool path for normal FTS freeform machining. However, it is extremely difficult to get the mathmatic expression for complex structured surface for example the bio-inspired micro/nano-structured surfaces. Indeed, micro/nano-structured functional surfaces are the result of a merging of surface geometry/form, surface features and textures. Surface features in a particular area are the entities that have specific functional properties. To expand the machining capability of FTS for structured surfaces, a feature-based tool path generation algorithm was developed to generate the point cloud of functional surfaces considering the distribution of surface features.

Taking a radiant pattern as an example, a single radiant pattern was designed with micro grooves distributed around a circle (figure 2(a)). The pattern can then be designed with specified spacing in both horizontal and vertical directions. The feature-based tool path generation was realised by converting the functional surface patterns into grey map data set (figure 2(b)) and then mapping the machining depth value according to the designed heights of surface features (figure 2(c)). After the mapping, the whole surface was sampled into a high density point cloud data set in a density point cloud data set according to user-specified radial and angular intervals. The radial and angular intervals were determined according to the smallest feature of functional surfaces. The sampled point cloud data set is the actual transformation of the designed structured surface.

To improve the scalability of design FTS system, the HUDCNC was designed to be capable of processing up to 5 million points in a single cutting loop. For a workpiece of 10 mm diameter, a radial sampling distance of 2 μm (angle sampling interval kept at 0.18°) can be achieved. In FTS patterning, the cutting tool path is in a shape of spiral and the HUDCNC controls the cutting tool position by generating the instant value of FTS movement through the interpolation of the point cloud data set at a fixed rate of 2 kHz. It is important to notice that, in principle, almost all kinds of patterns that can be described by grey maps could be generated by the proposed method if the frequency range of cutting tool movement is within the working range of the FTS system i.e. the maximum stroke and frequency of a generated cutting tool path is within the frequency-stroke curve of the FTS system. Typical examples are shown in section 3.

Table 1. Specifications of the measurement sensor.

| Specification        | Value                        |
|----------------------|------------------------------|
| Measurement range    | 100 μm                       |
| Repeatability        | 9 nm over 100 μm             |
| Probe to surface angle | 90° ± 45°                  |
| Measurement rate     | 2 kHz                        |
2.3. Integrated feature-based surface characterisation

To allow fast on-machine surface measurement and assessment, typical feature-based surface characterisation algorithms were employed as a toolkit in the developed closed-loop FTS machining system. A variety of data pre-processing, segmentation and feature analysis methods have been identified and used to decompose the FTS machined surface topography into different surface components either by height, scale or features, etc and associated for its application. A general procedure is illustrated in figure 3 and more details can be found in the book [17].

2.3.1. Pre-processing

Stochastic noise and measurement artefacts (batwings, spikes and voids) observed in optical measurement results will alter feature boundaries. Pre-processing operations/filters are performed on surface topography data for denosie purpose. Basic data levelling, thresholding, and filters such as Gaussian, PDE, Median filter etc [22] were developed to pre-process the OMSM data.

2.3.2. Segmentation

After pre-processing, the surface topography was divided into distinct features by applied segmentation methods. A rule is that every point of the surface can only belong to one feature. Because the OMSM data is scalar field’s data, the following segmentation methods are identified and used in this study including Sobel edge detection, thresholding, watershed segmentation with Wolf pruning [17, 23]. To obtain the regularity information of features, the areal autocorrelation function (AACF) analysis [24] was adapted and integrated into the process chain.

2.3.3. Feature property analysis

Once features have been identified and isolated by segmentation operations above, the individual features were analysed and characterised in terms of their attributes. There are two types of attributes as described in ISO 25178-2 [16]: the attributes of the
features themselves (e.g. feature size, height, area, volume shape, etc) and those discrping the relationships between features (position to a datum, orientation, density of features, etc).

2.4. Closed-loop processing chain for structured surfaces

Figure 4 shows the whole processing chain of proposed FTS patterning and OMSM of functional structured surface. To verify the developed feature-based FTS patterning and characterisation system, a series of experimental work was designed. The workpiece material is brass and is mounted on the machine work spindle. The balanced spindle radial error P-V value is less than 15 nm at the zero plane. The FTS tool holder and OMSM probe are mounted on the Z slide. To avoid any form distortion caused by the misalignment of cutting tool position and the spindle centre line, both the diamond cutting tool and the measurement probe were aligned with the spindle center before carrying out the FTS machining and OMSM. A cutting tool setting method was developed based on the integrated OMSM system [11]. Less than 1 μm tool alignment accuracy was achieved in this study, which is much smaller than current integrated camera version based tool alignment methods (normally at a level of 3–5 μm).

In total, four different types of structured surfaces were designed: periodic structured surfaces, tessellations, biological surfaces, profile and character combinations. A single point diamond conical tool of tip radius 0.1 mm was used in FTS surface structuring. All structured surfaces were fabricated under a constant spindle speed of 120 rpm and feedrate of 5 μm/rev. After each cutting path, the integrated OMSM was used to collect surface information and generate OMSM raw data. The OMSM sampling rate was fixed at 2 kHz under spindle speed of 120 rpm and feedrate of 2.5 μm rev⁻¹. It takes about 8.5 min for machining and another 17 min to scan the machined surface with a diameter of 10 mm. Since most areal topography analysis algorithms are requiring surface height information at uniformly spaced locations (points) arranged on a rectangular lattice, the OMSM raw data was converted into the standard SDF file accordingly. The SDF file was then analysed by the integrated surface characterisation algorithms to get more detailed surface feature information.

A general procedure to process the on-machine measurement data was proposed and implemented in the developed processing chain. The method basically includes following steps to characterise the OMSM data:

• Step 1: define the region of interest;
• Step 2: level the data;
• Step 3: robust low-pass filter to remove the high frequency noise and measurement outliers;
• Step 4: segmentation and pattern analysis to decompose the structured surface topography;
• Step 5: feature analysis to characterise the feature attributes.

3. Results and discussion

3.1. Periodic structured surfaces

Honey comb is a typical structured surface and is essentially a surface with periodic distributed hexagon features. The primary geometric attributes comprise:
hexagon height, area and feature spatial relationships e.g. the regularity of feature distribution.

Through the pre-processing, the spikes and tool marks left on the surface were successfully removed while keeping the important surface geometrical features (figure 5(b)). The geometrical information of each individual hexagon feature can then be exacted and analysed through various segmentation operations. To analyse the regularity of machined periodic structured surface, the AACF method was used to obtain the information of feature distribution. As shown in figure 5(c), the lattice reconstructed from the peak point (red colour) of the AACF indicated the spacing of each hexagon feature. The regularity of the structures can then be assessed by comparing with the original designed surface.

Moreover, watershed segmentation, Wolf pruning and Sobel edge detection operations were used to separate the whole honey comb into individual hexagon features (figure 5(d)). The geometrical properties of each individual hexagon such as the average, deviations, the peak and valley value, area value and the local peak to valley height (Pt) within a surface feature can be quantified as shown in figure 5(e). The mean value of Pt is 5.565 μm which is 435 nm short of designed specifications, indicating that the form deviations of all hexagons are less than 450 nm. Those information can be used to guide the development of potential solutions to improve the FTS machining accuracy.

3.2. Tessellated surfaces

Tessellated surfaces refer to topographies with periodic regular patterns. The FTS machining of tessellated surfaces is very challenging because the complexity of patterns and surface features potentially
require very accurate and quick response of tool motion control. For surface characterisation, the robustness of the surface analysis approach depends on how a unit tile (or primitive cell) is specified, isolated and reconstructed into the network of cells. Different index factors/values might be required for segmentation and feature identification. The surface characterisation of tessellated surfaces detailed in [17] was applied to analysis two typical tessellations, i.e. radiant patterns and penrose tiling generated by the developed FTS system.

Figure 6(a) shows the on-machine measurement results, and the regularity of the period of radiant patterns was accessed by AACF. The lattice points are in a triangular array with a spacing of 1.764 mm in figure 6(b) indicating the periodic distribution feature of the radiant structured surface. To obtain detailed geometrical properties of individual pattern, a radiant pattern was selected and figure 6(d) shows the segmentation result of the topography using watershed segmentation with 5% Wolf pruning combined with Sobel edge detection. The results indicated that the radiant pattern was effectively separated into different groove regions and each groove’s dimensional information such as region averaged height, peak value and valley, Pt and area can be calculated as listed in figure 6(e). Although the pattern looks good in figure 6(c), the variation of rendered colour in a single groove (figure 6(d)) and the fluctuation of Pt value (figure 6(e)) indicated the structure defects of the identified groove.

Another typical tessellated surface is Penrose tiling which was designed to consist feature geometries of different shapes and heights as shown in figure 7.
was found that AACF cannot identify the regularity of this tessellation (figure 7(b)). Figure 7(c) shows the extracted central area after thresholding on the feature heights. Each feature is rendered using a different colour and the dark blue lines are boundaries separating adjacent features. Segmentation result is shown in figure 7(d). As compared with the simple thresholding, more detailed information of each feature can be obtained.

Figure 7. Surface characterisation of features on a Penrose tiling: (a) OMSM raw data; (b) AACF result; (c) extracted central area after thresholding; (d) segmentation of Wolf punching 5%.  

Figure 8. FTS machined snake skin topography analysis: (a) OMSM raw data; (b) measurement results of region A in (a); (c) segmentation; (d) AACF analysis and (e) cross-sectional view of AACF along B-B' line in (d).
3.3. Biological surfaces

The amazing functional properties of biological surfaces (e.g. skins of animals, fish, insects, leaves of plants etc) are enabled by their surface structures. Those biological structures are mimicked by engineered topographies to achieve targeted surface functionalities [1, 2]. It is recognised that the scales on a snake skin can reduce drag function when wriggling up various surface conditions. Engineering mimicked scale snake skin by laser patterning can be found in [25]. However, the laser machined engineered topographies are quite different from the scale pattern of the nature snake skin.

The proposed closed-loop FTS machining has added advantages to generate snake skin pattern from a real snake skin picture as shown in figure 8. For a natural snake skin, there are high similarity of skin scales but each scale shape may vary considerably from the segmentation result (figure 8(c)). The significant peaks in each segment allowing further analysis, for example, a height analysis can identify which area of snake scales are actively contact with the land and play the key role in drag reduction. The regularity of local distribution of scales can be identified from the AACF analysis (figure 8(d)). Moreover, hybrid parameters (Sdq, Sdr) and volume parameters (Vmp, Vmc, Vvc, Vvv) [16] can be calculated as indicators of these surface areas and associated with the drag reduction functionality.

3.4. Profile and characters

To demonstrate the flexibility of proposed FTS patterning method, a profile of Shakespeare and his poems were desigend and fabricated as shown in figure 9. The surface topography is a combination of deterministic characters and stochastic profile. Edge identifications can be used to extract the characters. The critical points, lines and areas of character lines can be identified and extracted to be analysed by using the proposed surface characterisation toolkit (figure 9(c)).

Although energy-beam-based method for example laser-assisted surface patterning can process similar patterns, the proposed closed-loop feature-based
FTS patterning and characterisation provide an effective solution to achieve the deterministic generation of this kind of stochastic-deterministic profile. This could be inspiring to the design, fabrication and characterisation of functional integrated structured surfaces in the future.

4. Conclusion

A closed-loop feature-based FTS patterning and surface characterisation platform has been developed to generate complex functional structured surfaces. The whole FTS machining and measurement process was controlled by a self-developed controller with functional modules covering feature-based tool path generation, FTS patterning, on-machine surface topography sampling, and data formatting. A procedure for fast on-machine surface characterisation was proposed and a toolkit of feature-based surface characterisation was integrated into the closed-loop FTS processing chain of micro/nano-structured surfaces. The performance of the developed platform has been well-demonstrated through generating of four different types of functional structured surfaces including periodic structures, patterns and tessellations, biological surfaces, profile and character combinations.

The novelty of the proposed feature-based tool path generation lies in the transformation of surface features to cutting tool path through the mapping between grey map and designed feature dimensions. The high flexibility of proposed tool path planning method and the high accuracy of OMSM-based tool-workpiece alignment significantly improve and expand the machining capability of FTS machining of structured surfaces. It provides a solution of practical importance to address the challenge on deterministic generating complex structured surfaces especially biological functional structured surfaces and other combinations. The scalability of proposed FTS patterning technique could be further improved by adaptively optimising the tool path interpolation and using customised/special designed diamond cutting tool-tips.

The integrated OMSM system and feature-based surface characterisation (FBSC) toolkit allow the fast in-line assessment and quality control of ultra-precision FTS machining. Both individual surface feature and their relationships can be evaluated following the procedure of proposed surface characterisation method. Those information are valuable to establish the link between surface geometries, machining parameters and surface functionalities. Challenges have been identified when using AACK for tessellations of multi-features. For the applied segmentation method, it remains difficult to accurately calculate feature geometrical properties for non-regular surface structures.

In summary, the non-stop manner of the developed FTS-OMSM-FBSC system will allow more complex functional structured surfaces to be designed and tested in short lead time. It provides a promising technical solution to further improve the efficiency and accuracy of ultra-precision FTS machining as well as its automation level.

Acknowledgments

The authors gratefully acknowledge the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 767589, the UK’s EPSRC funding of Future Metrology Hub (Ref: EP/P006930/1) and STFC Innovation Partnership Scheme (STFC-IPS) project under grant agreement No. ST/V001280/1.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Zhen Tong @ https://orcid.org/0000-0003-3138-1515

References

[1] Malshe A P, Bapat S, Rajurkar K P and Haitjema H 2018 Bio-inspired textures for functional applications CIRP Ann. 67 627–50
[2] Malshe A, Rajurkar K, Samant A, Hansen H N, Bapat S and Jiang W 2013 Bio-inspired functional surfaces for advanced applications CIRP Ann. 62 607–28
[3] Brinksmeier E, Karpuschewski B, Yan J and Schönemann L 2020 Manufacturing of multiscale structured surfaces CIRP Ann. 69 717–39
[4] Zhang S, Zhou Y, Zhang H, Xiong Z and To S 2019 Advances in ultra-precision machining of micro-structured functional surfaces and their typical applications Int. J. Mach. Tools Manuf. 142 16–41
[5] Fang F Z, Zhang X D, Weckenmann A, Zhang G X and Evans C 2013 Manufacturing and measurement of freeform optics CIRP Annals - Manufacturing Technology. 62 823–46
[6] Patterson S and Magrab E 1985 Design and testing of a fast tool servo for diamond turning Precis. Eng. 7 123–8
[7] Weck M, Oezmurali H, Mehlikopp K and Terwey T 1995 A new hybrid concept for a long stroke fast tool servo system Proc of ASPE pp 211–4
[8] Lu X-D and Trumper D L 2005 Ultrafast tool servos for diamond turning CIRP Ann. 54 383–8
[9] Brinksmeier E et al 2010 Submicron functional surfaces generated by diamond machining CIRP Ann. 59 533–8
[10] Zhu Z, Tong Z, To S and Jiang X 2019 Tuned diamond turning of micro-structured surfaces on brittle materials for the improvement of machining efficiency CIRP Ann. 68 559–62
[11] Tong Z, Zhong W, To S and Zeng W 2020 Fast-tool-servo micro-grooving freeform surfaces with embedded metrology CIRP Ann. 69 505–8
[12] Li D, Jiang X, Tong Z and Blunt L 2019 Development and application of interferometric on-machine surface measurement for ultraprecision turning process Journal of Manufacturing Science and Engineering, Trans. of the ASME 141
[13] Li D, Tong Z, Jiang X, Blunt L and Gao F 2018 Calibration of an interferometric on-machine probing system on an ultraprecision turning machine Measurement: Journal of the International Measurement Confederation. 118 96–104
14] ISO. ISO 16610-85 2013 Geometrical Product Specification (GPS)—Surface texture: —Filtration —Part 85: Profile Morphological: Segmentation (Geneva, Switzerland: International Organization for Standardization) 2013

[15] ISO. ISO 16610-45/DIS 2020 Geometrical Product Specification (GPS— Surface texture: —Filtration — Part 45: Profile Morphological: Segmentation (Geneva, Switzerland: International Organization for Standardization) 2020

[16] ISO. ISO 25178-2 2012 Geometrical Product Specification (GPS) — Surface Texture — Part 2: Terms, Definitions and Surface Texture Parameters, (Geneva, Switzerland: International Organization for Standardization) 2012

[17] Jiang X and Scott P J 2020 Advanced Metrology: Freeform Surfaces (New York: Academic)

[18] Li D, Wang B, Tong Z, Blunt L and Jiang X 2019 On-machine surface measurement and applications for ultra-precision machining: a state-of-the-art review Int. J. Adv. Manuf. Technol. 104

[19] Gao W et al 2019 On-machine and in-process surface metrology for precision manufacturing CIRP Ann. 68 843–66

[20] Jiang X, Tong Z and Li D 2020 On-machine measurement system and its application in ultra-precision manufacturing ed Z Jiang and S Yang Precision Machines. Singapore (Singapore: Springer) pp 563–99

[21] Li D, Jiang X, Tong Z and Blunt L 2018 Kinematics error compensation for a surface measurement probe on an ultra-precision turning machine Micromachines. 9 334-

[22] Zeng W, Jiang X and Scott P J 2010 Fast algorithm of the robust Gaussian regression filter for areal surface analysis Meas. Sci. Technol. 21 055108

[23] Scott P J 2004 Pattern analysis and metrology: the extraction of stable features from observable measurements Proceedings of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences. 460 2845–64

[24] Zeng W, Jiang X and Blunt L 2009 Surface characterisation-based tool wear monitoring in peripheral milling Int. J. Adv. Manuf. Technol. 40 226–33

[25] Greiner C and Schafer M 2015 Bio-inspired scale-like surface textures and their tribological properties Bioinspir Biomim. 10 044001