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ORIGINAL ARTICLE

On-machine surface measurement and applications for ultra-precision machining: a state-of-the-art review

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Abstract

Surface measurement is essential to enhance accuracy and efficiency in ultra-precision machining. In order to increase the measurement availability and efficiency, offline lab-based solutions are shifting towards the use of surface metrology upon manufacturing platforms. With the lack of remounting errors, on-machine surface measurement (OMSM) allows the deterministic assessment of manufactured surfaces just-in-time and also provides valuable feedback to the process control of ultra-precision machining. This paper is aimed at reviewing the state-of-the-art OMSM and applications in the ultra-precision machining process. The benefits and considerations on the integration of metrology are discussed. The merits and limitations among different OMSM types are compared as well. Finally, the challenges and outlook of the ultra-precision machining-metrology integration are highlighted.

Keywords On-machine surface measurement · Metrology · Ultra-precision machining · Machining-metrology integration

1 Introduction

Ultra-precision machining is promising to generate surfaces with sub-micrometric form accuracy and nanometric surface roughness, which are highly demanded in optical, biomedical, electronic and aerospace industries [1, 2]. However, many external factors still cause surface deviations from the design, involving environmental factors, machine structural errors, vibration and thermal deformation [3–5]. The measurement and characterisation process becomes the key to evaluating the machined surface quality and further improving machining processes [6, 7]. Surface metrology instrumentation has made great progress with the development of new principle, mathematical algorithm and high-precision sensors [8–10]. For some demanding advanced manufacturing, such as large telescope optics polishing [11] and reel-to-reel thin film fabrication [12], offline or post-process measurement is not applicable any more. Furthermore, the errors induced by removal and remounting of workpieces cannot be neglected in high-precision applications and would deteriorate the surface quality if re-machining processes need to be carried out [13].

In order to increase the measurement availability and efficiency, offline lab-based solutions are shifting towards the use of surface metrology upon manufacturing platforms [6, 8, 14]. The application of integrated measurement will significantly contribute to ultra-precision manufacturing in a cost-effective and environmentally sustainable manner [6, 15, 16], which not only allows the direct assessment of machined surfaces just-in-time but also provides feedback to the process control for further compensation and optimisation.

This paper will present a comprehensive review of state-of-the-art on-machine surface measurement (OMSM) and applications in the ultra-precision machining process. Firstly, the benefits and considerations on the integration of metrology are discussed. Then, the merits and limitations among different OMSM types are compared. Finally, the challenges and opportunities associated with OMSM in ultra-precision machining process are proposed with several key conclusions.

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2 Definition, advantages and considerations for OMSM

2.1 Definition of OMSM

Vacharanukul and Mekid [17] provided a nomenclature classification for the act of measurement during the manufacturing process in three groups, namely in-process, in situ (on-machine) and post-process.

In-process measurement refers to the act of measurement performed while the manufacturing process continues. It can be fully integrated into the process control system to provide real-time information for the manufacturing process. A typical example of in-process measurement can be found in the monitoring and measurement of fast moving films in the flexible electronics roll-to-roll manufacturing process [18]. However, many challenges for in-process measurement have to be overcome, such as the effect of machining vibrations, heat flux and presence of lubricants and swarf. Up to now, these challenges greatly limit the application of in-process measurement into ultra-precision machining processes.

In situ measurement, also known as on-machine measurement, is defined as measuring the surfaces without the removal of the workpiece from the machine tool. The machining process is usually paused before the measurement process. Compared with in-process measurement, on-machine or in situ measurement operates in a relatively mild and static environment without cutting forces and thermal effect, which significantly relaxes the stringent requirements for implementation. Although the machining throughput rate is decreased to some degree, the automation level will be increased with the integration of on-machine measurement. In this review, the term, on-machine surface measurement (OMSM), is used to distinguish on-machine measurement of other physical quantities (such as forces, temperature and power consumption). This work is aimed at reviewing the state-of-the-art OMSM and their applications in the ultra-precision machining process.

Post-process measurement, also called offline measurement, is a standard inspection in the production process. The workpieces need to be removed from machine tools and transported to the offline measurement instruments, which are usually located in a temperature-controlled and anti-vibration environment. Post-process measurement is time consuming and the transportation process is risky particularly for large-scale precision components. Furthermore, in the ultra-precision level, the errors induced by removal and remounting of workpieces cannot be neglected.

2.2 Benefits of OMSM

The obvious benefit of OMSM is that there is no need to transport workpieces between the machining and measurement platforms. Also, the machine tool axes are utilised to accommodate the measuring range, which means the machined components can be always measured within the machine tool volume. Therefore, from the production perspective, the metrology integration increases the inspection efficiency, production throughput and reduces the cost associated with transportation labour and tools.

Secondly, the automation level of manufacturing is greatly elevated with the application of OMSM. The intimate knowledge of measurement strategy and other operation experiences can be effectively integrated into the manufacturing control system. Moreover, the machined surface can be inspected in situ and the extracted information is promptly fed back to the process control for further decisions. OMSM is considered indispensable for the autonomous and intelligent manufacturing [6].

Thirdly, with the integration of OMSM, the coordinate system between machining and measurement is kept consistent through the whole manufacturing process. This is particularly important for the ultra-precision freeform machining processes. As the form tolerance is within the sub-micrometre and even nanometre range, the errors induced by removal and remounting are considerable. The realignment operation would inhibit re-machining processes for defects repair and deterministic compensation. Zhang et al. [13] concluded that even small angle errors introduced in remounting would cause significant large shape deviation. By means of simulation of a sinusoidal grid surface, 0.1° angular error in roll, pitch and yaw resulted in 0.1-mm peak to valley surface error, as illustrated in Fig. 1.

However, there are also some issues emerging with the integration of surface measurement on the machine tool. On-machine inspection will cause the loss of machining availability, which reduces the production throughput in large-scale manufacturing, although the metrology integration increases

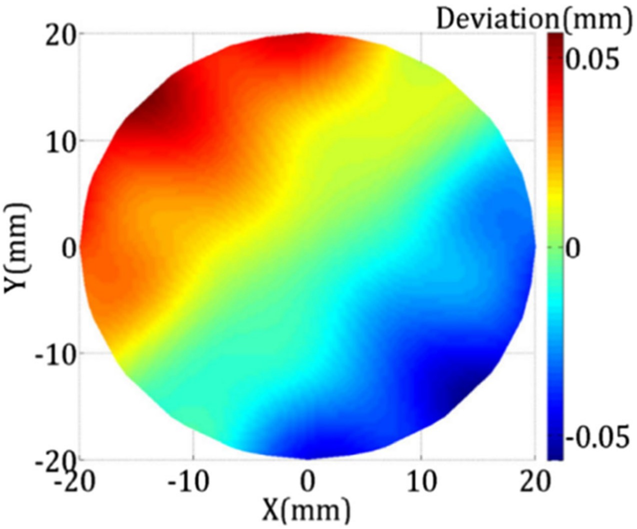


Fig. 1 Surface deviations caused by the angle errors in remounting [13]

the inspection efficiency without re-clamping process. Also, the measurement coordinate frame is integrated into the machine tool. The machine axis kinematic error and thermal effect will deteriorate the measurement result to some extent.

2.3 Considerations for OMSM integration

In order to apply OMSM successfully, there are several technological gaps to be bridged for the shift from laboratory-based measurement systems to the integrated metrology. The consideration for OMSM integration is summarised in Fig. 2.

First of all, the precision and dynamic range of the selected measurement instrument should meet the specific requirement for the corresponding machining process. Particularly for ultra-precision machining applications, the precision requirement for measurement is demanding, which should lie in the nanometric level. Since operating in the machine tool environment, the instrument needs to be robust to the presence of vibrations, temperature and other environmental disturbance. These factors should not adversely affect the quality of the measurement result. High measurement rate is also preferable, which helps alleviate vibration effects and increase the inspection efficiency. In addition, compact design tends to increase the robustness of the system and is required if the working volume is limited. To promote the OMSM applications in advanced manufacturing, the cost of the additional functionality needs to be taken into account as well.

Besides the considerations from the instrumentation perspective, the integration process into the manufacturing environment will lead to further challenges, such as the establishment of the measurement coordinate, scanning strategies, calibration methodology and closed-loop operations. For example, machine tool factors such as vibration and machine tool errors would have a significant effect on the overall measurement performance. Vibration during the measurement is detrimental to the measurement results. Moreover, as surface measurement is actuated by the machine tool stages, kinematic errors must be compensated to acquire reliable surface information. It is possible that for commercial machine tools, some kinematic errors have been compensated by machine tool manufacturers. However, the error data is not usually shared. OMSM developers have to measure and compensate those errors independently according to their specific tasks. Li et al. [19] proposed a systematic calibration scheme for single-point OMSM for ultra-precision machining process. Three primary errors, including machine-induced vibration, machine tool kinematic errors and embedded sensor linearity errors, were calibrated, as shown in Fig. 3.

The relationship between OMSM sampling frequency, external vibration frequency and scanning parameters was analysed theoretically [19]. A frequency decision graph illustrated in Fig. 4 is generated based on Nyquist sampling theorem to guide how to select adequate sampling frequency and scanning parameters. The OMSM sampling frequency is required to be at least 2 times the machine-induced vibration frequency to avoid aliasing. The induced vibration components into the OMSM acquisition can be filtered out for accurate surface characterisation.

In addition, OMSM scanning is often carried out by the machine tool axes motion. The deviation from the programmed scanning path (known as kinematics error) will induce additional measurement errors because of axes' mechanical imperfections, wear of machine tool elements and axes misalignments. Therefore, machine tool kinematic error needs

Fig. 2 Consideration for OMSM integration

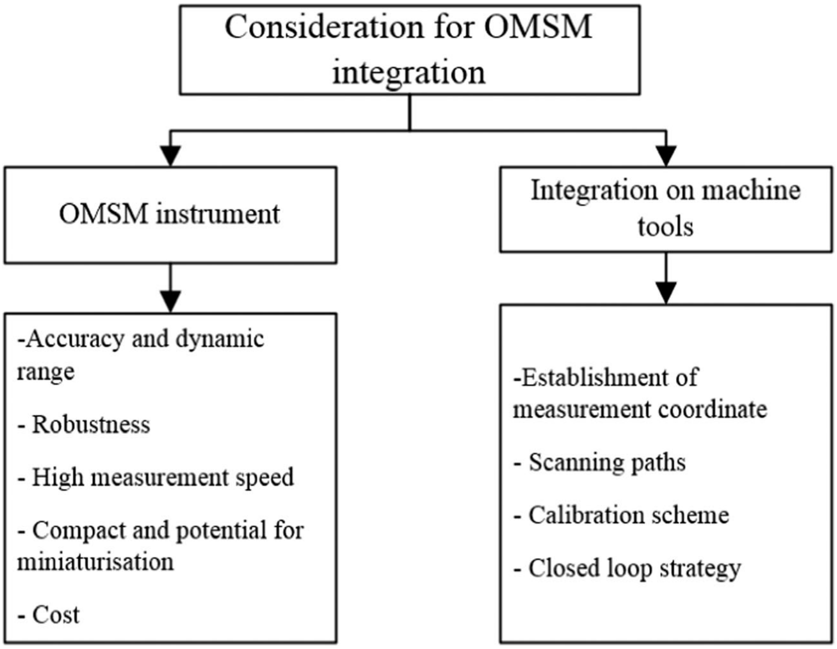
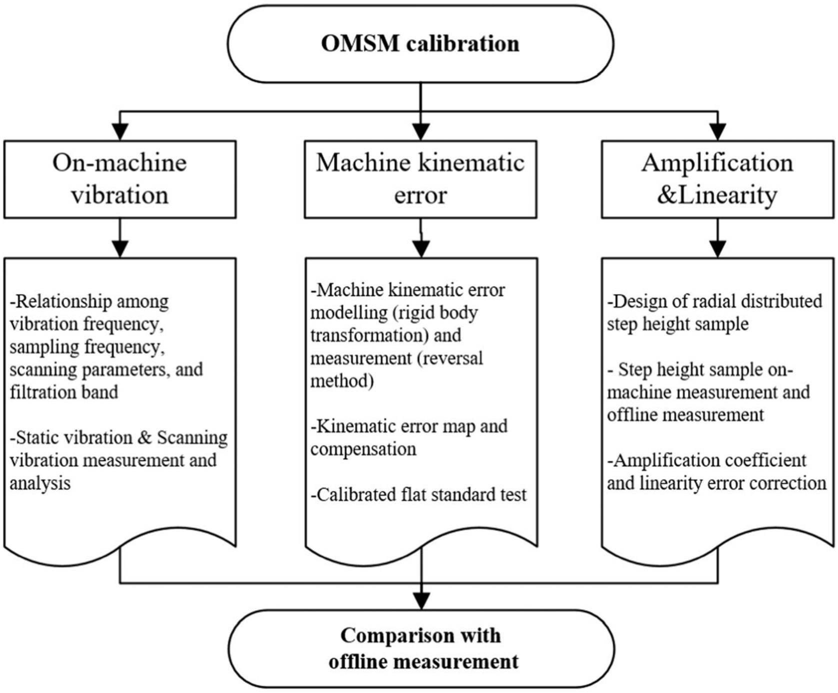


Fig. 3 Structure diagram of OMSM calibration [19]



to be mapped for OMSM correction with the proposed kinematics error modelling (based on rigid-body kinematics method) and measurement (based on reversal method) [20]. Gao et al. [21–23] conducted extensive research in separation of machine tool motion error (slide straightness and spindle error) and on-machine measured surface error (roundness error and axial profile error) with multiple points and reversal methodology. Calibration of the embedded sensor linearity error is important as well [24]. Li et al. [19] performed on-machine calibration by measuring a diamond-turned step height sample. After correction of slope coefficient, the linearity error was reduced from 93 to 14 nm. Finally, calibrated offline measurement needs to be carried out and compared with the on-machine results in order to prove the validity of the integrated OMSM.

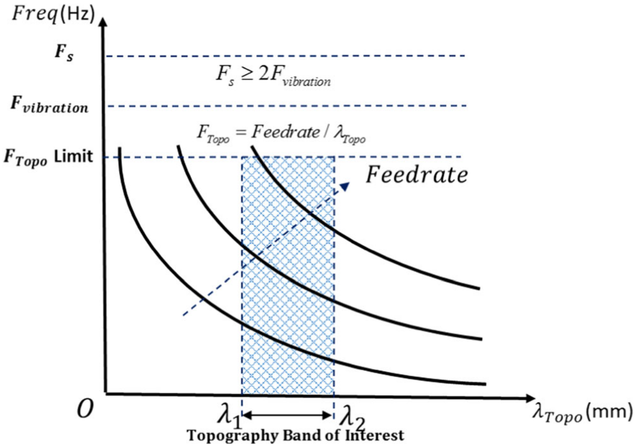


Fig. 4 Sampling frequency decision graph [19]

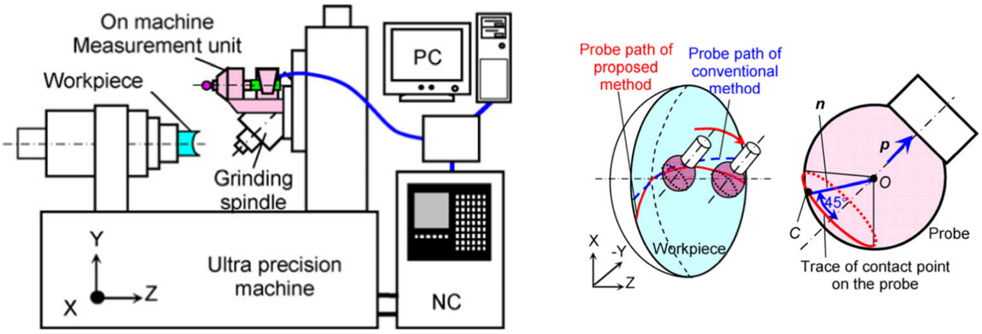
3 Review of OMSM instrumentation and applications

Because of the growing complexity and stringent requirement for products, it is necessary to form a closed-loop control of the manufacturing process. On-machine metrology has gained increasing attention from both industries and academia. Similar to offline measurement, OMSM can be classified into contact and non-contact optical types depending on the nature of probes [25]. The review in this section presents the state-of-the-art OMSM and applications for ultra-precision machining.

3.1 Contact OMSM and applications

Similar to laboratory-based coordinate measurement machines, the sensing probe acquires spatial coordinates of discrete points to represent the form and geometrical features. Contact probing is used for OMSM because of its technological maturity and ease of integration. The sensing probe acquires spatial coordinates of discrete points to represent the form and geometrical features. However, for on-machine applications, several modification and specific setup are often adopted, which makes the contact OMSM different from the offline contact measurement.

Suzuki et al. [26] developed a contact probe OMSM to measure steep aspheric optics on the ultra-precision grinding machine (shown in Fig. 5a). A ceramic air slider and high-accuracy glass scale were adopted in the probing unit for its low thermal expansion coefficient, light weight and high rigidity. The special tilted angle configuration made the contact



(a) (b)

Fig. 5 **a** Schematic of on-machine contact probing for optics grinding process and **b** tilted angle probe configuration [26]

probe keep the contact angle with the ground aspheric surface during the measurement process, in order to decrease the variation of probing friction force (shown in Fig. 5b).

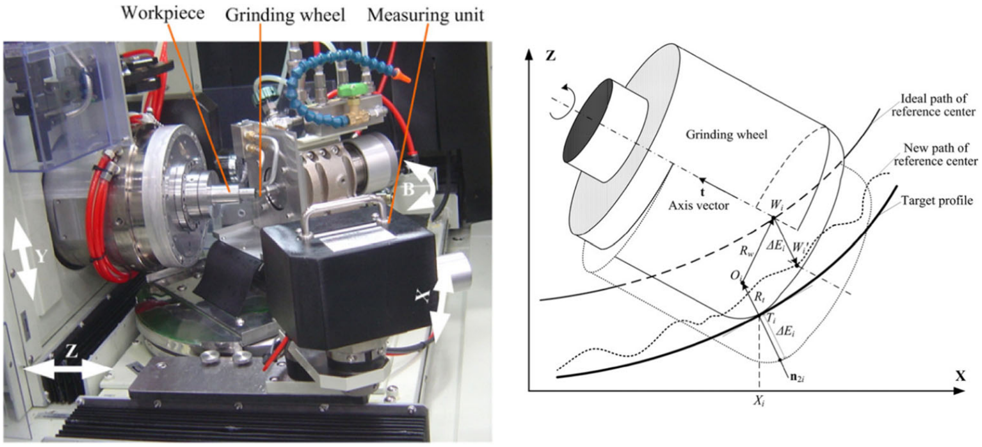
Chen et al. [27] employed a similar contact probing as OMSM and applied for the ultra-precision mould grinding (shown in Fig. 6a). The profile reconstruction based on the measured data showed that OMSM results agreed well with the off-machine commercial profilometre. The OMSM measurement result was then adopted to set up a new grinding tool path for error correction along the surface normal direction (shown in Fig. 6b). The proposed compensation grinding process achieved profile accuracy of 177 nm (PV) and surface roughness of 1.7 nm (Ra).

Contact probing systems are nowadays also provided as accessories in some commercial ultra-precision machining tools. For example, Moore Nanotech provides an on-machine measuring probing system, which is composed of a linear variable differential transformer (LVDT) sensor and air bearings [28]. Zhang et al. [13] combined this kind of on-machine and off-machine measurement results to increase the diamond machining accuracy for freeform optical surfaces. The on-machine contact measurement was utilised to align the remounting workpiece into the modified machining coordinate while surface error derived from offline measurement was used for compensation machining. The workflow and experimental setup are shown in Fig. 7a and b, respectively.

The conventional contact probing utilises a ruby ball. The probe radius often lies in the millimetre range, which greatly limits the measurement lateral resolution. Scanning probe microscopes (SPMs) with finer tips are developed to measure ultra-precision machined micro-structures on the machine tool. For instance, Gao et al. [29] specially designed an atomic force microscope (AFM) head to inspect diamond-turned microstructures. A robust linear encoder was adopted in the AFM head to measure profile height in the presence of electromagnetic noise (Fig. 8). The OMSM system was able to measure micro-structured surfaces with 0.5-nm resolution in a spiral path.

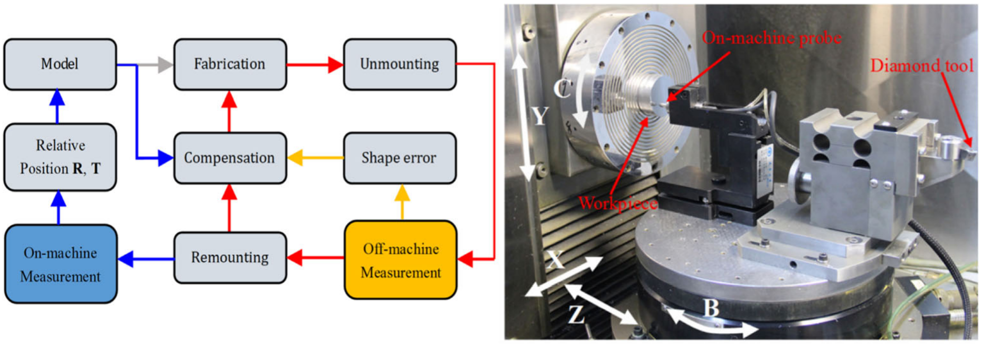
Ju et al. [30] developed a scanning tunnelling microscope (STM) probing system and an ultra-sharp tip with a high aspect ratio of 450:1 was used. The STM-based probing system was mounted on the main spindle of an ultra-precision turning machine and employed to assist the precision fabrication of rectangular pyramid arrays (shown in Fig. 9a). Resulting from the feedback of on-machine measurement, the form accuracy of high-slope micro-structures was significantly improved by cutting depth compensation [31].

The same probing system was also employed to measure 3D curved compound eye surfaces machined by slow tool servo (STS) technique [32]. In this case, the measurement unit



(a) (b)

Fig. 6 **a** Mould grinding machine with integrated probing unit and **b** schematic of compensation grinding strategy [27]



(a) (b)

Fig. 7 **a** Workflow of combination of on- and off-machine measurement. **b** Experiment setup of on-machine measurement [13]

was mounted in the *B* axis, as illustrated in Fig. 9b. A tip-tracking strategy was proposed to extend the measuring ranges with more flexibility. Distortion related to the centring error was analysed based on the characterised points. Through the evaluation of OMSM results, the main machining errors were identified as inaccuracy of tool radius and the uncompensated region around the inflection points.

Noh et al. [33] and Lee et al. [34] innovatively integrated a piezoelectric force sensor into the fast tool servo (FTS) device, which constituted a force-displacement servo unit termed as FS-FTS. FS-FTS acted as a cutting tool and force sensor during machining, while it was employed as a contact probe after machining. The particular characteristic enabled the unit to perform structured surface machining, profile measurement, defect identification and cutting tool reposition.

With the assistance of FS-FTS, Chen et al. [35] proposed an in-process identification and repair of diamond-turned micro-lens arrays on the roller mould. Thrust force was monitored during the machining process of the micro-structures, in order to indicate the cutting status and map singular forces with respect to the cutting tool position. After the defects were identified by FS-FTS scanning, the repair process was subsequently carried out, as illustrated in Fig. 10.

Furthermore, the concept of relay fabrication [36] was realised with the capability of repositioning a new tool to the former cutting spot after the replacement of the worn tool. The schematic of such process is illustrated in Fig. 11. A bidirectional scanning method was adopted to increase the positioning accuracy due to the delay of the feedback control loop. The feasibility of the OMSM and tool positioning method were demonstrated by stitching machining of a micro-groove array and filling fabrication of a micro-lens pattern.

Table 1 summarises state-of-the-art researches on the contact type of OMSM and corresponding applications in ultra-precision machining processes.

3.2 Non-contact optical OMSM and applications

Ultra-precision machined surfaces can be also measured on-machine by non-contact optical measurement methods. The non-destructive and fast capturing nature makes them suitable for OMSM.

Particularly for ultra-precision machining processes, on-machine interferometry has received a lot of attention from researchers for its nanometric precision. Nomura et al. [37] developed a common path lateral-shearing interferometer on

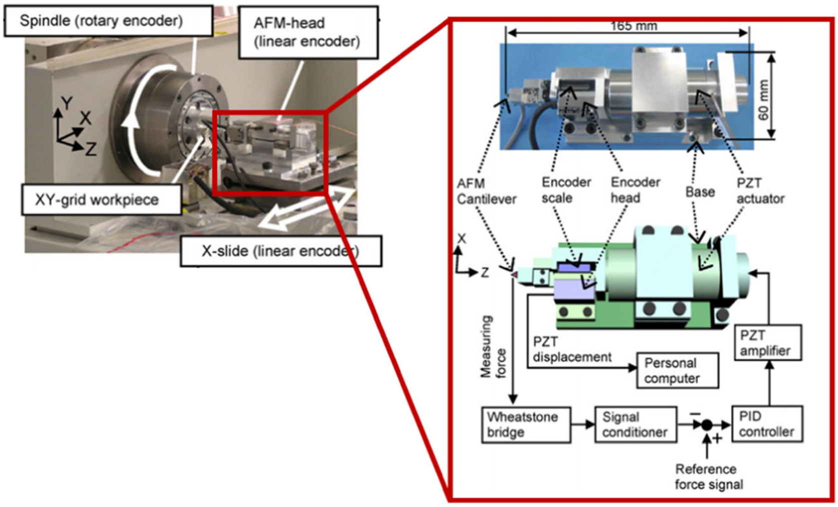
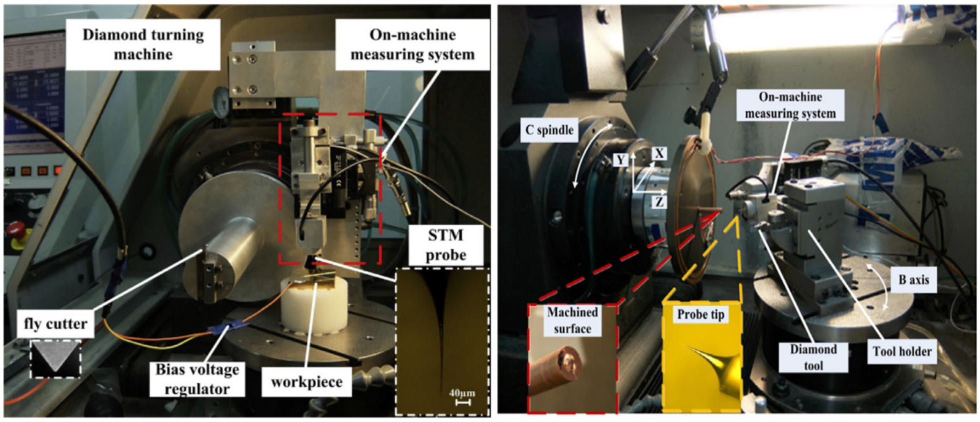


Fig. 8 Robust AFM based on-machine measuring system [29]

Fig. 9 **a** STM on-machine measurement applied in fly-cutting of V grooves [31]. **b** In-tool servo machining of 3D compound eye structures [32]



(a) (b)

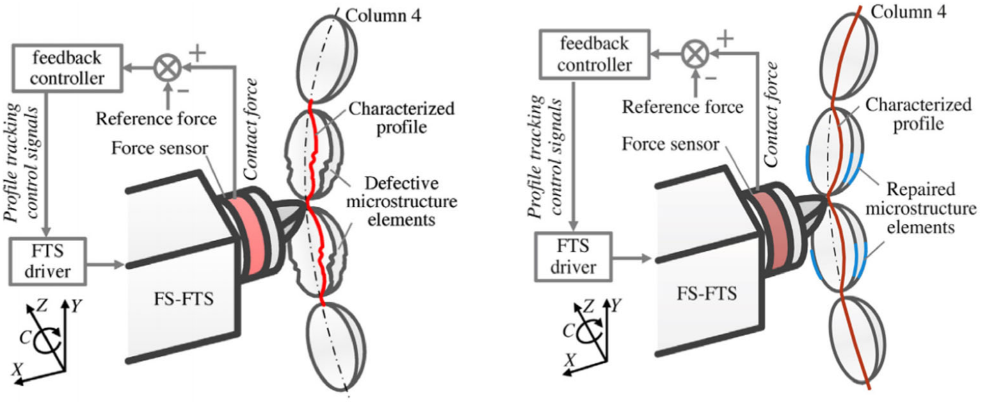
a diamond-turning machine because the configuration was insensitive to the vibrations and air turbulence. A plane parallel plate was adopted to shear the wave front under test in the interferometer. In order to measure spherical and aspherical surfaces, computer-generated hologram zone plates were added. The schematic and the experimental setup of on-machine shearing interferometer are respectively illustrated in Fig. 12a and b. Experimental results showed the interferometer was sufficiently stable to be applied in diamond-turning process with an accuracy of 0.06 μm PV, even when the machine tool spindle was running at 1000 rpm.

Shore et al. [38] investigated on-machine measurement for the diamond-turned MIRI spectrometer mirrors, in order to avoid error-prone replacement and alignment of the workpiece. To measure the form accuracy of individual mirror segments, a Twyman-Green type PSI was mounted on a 3-axis ultra-precision machine with sub-micron positioning ability. The measurement setup is illustrated in Fig. 13. This measurement repeatability was characterised as 1.9 nm (normally distributed). As the MIRI mirror was comprised of several discrete segments, the interferometer head was additionally scanned in three directions to establish the confocal position and coordinate for each segment. The centres of curvature and relative location for the mirror segments were subsequently derived.

As a variation of traditional PSI, dynamic interferometry is developed as a single-shot spatial phase–shifting method [39]. Four phase-shifted interferograms can be simultaneously generated through the use of a quarter wave plate and a pixelated birefringent mask in front of a single detector. The principle is shown in Fig. 14. The single-shot nature of the dynamic interferometry allows fast surface measurement without sensitivity to vibration or air flow through interferometer paths.

With such preferable characteristics, King et al. [40] proposed an integrated polishing and in situ measurement of large-aperture optics up to 1 m in diameter. As shown in Fig. 15, it consisted of a Zeeko IRP 1000 polishing machine and a 4D dynamic interferometer with a multi-axis stage. The large optics were measured in situ without the need of risky transportation to offline metrology platforms and corrective polishing was subsequently carried out. The measurement system was also equipped with different CGH elements to measure aspheric and freeform optics. Besides, a microscopic interferometer for texture measurement and a laser tracker for radius measurement can be integrated on-machine as optional accessories.

Fig. 10 Micro-lens defect identification (**a**) and repair process (**b**) with FS-FTS [35]



(a) (b)

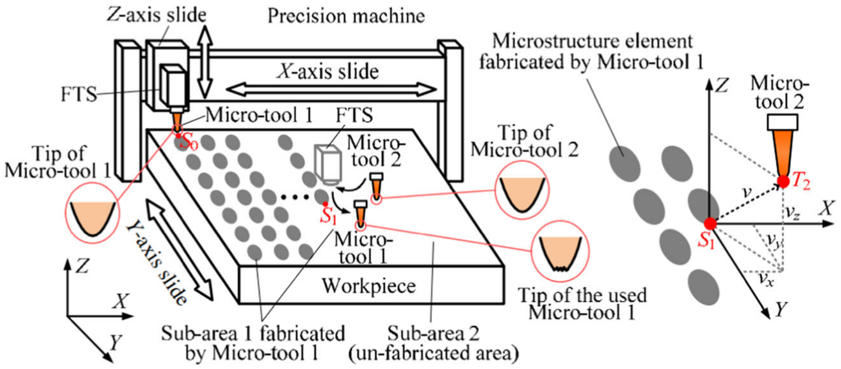


Fig. 11 Schematic of tool tip position measurement and relay fabrication of micro-structures with FS-FTS [36]

Li et al. [19] integrated a single-point robust interferometric sensor onto an ultra-precision turning machine (as shown in Fig. 16). The sensor was a dispersed reference interferometry (DRI), based on the principle of a Michelson interferometer with chromatic dispersion added in the reference arm and resulting in a wavelength-dependent optical path length. Optical fibre–based implementation was enabled due to the adoption of the low coherence source and led to the potential for remote configuration and miniaturisation [41]. In order to increase the fidelity of measurement results, the calibration scheme of the system was proposed. As the consistency between machining and measurement coordinate system was preserved, the derived surface error from OMSM was directly fed back to the corrective operation through modification of the machining tool path. A corrective machining experiment with the aid of OMSM improved the profile accuracy (Fig. 17) (approximately 44%) of a diamond-turned cosine wave sample (5-μm amplitude and 2.5-mm wavelength) [42].

In terms of micro-scale topography measurement, a wavelength scanning interferometer (WSI) based on wavelength division multiplexing has been developed for the measurement of diamond machined-structured surfaces on a large drum-turning machine [43]. For the integration in a noisy manufacturing environment, vibration sensitivity issue was addressed by use of a reference interferometer multiplexed into the measurement paths. Figure 18 illustrates a reference

Table 1 Contact type of OMSM and application

No	Author/year	Principle	Instrument	Performance	Application	Remarks
1	Suzuki et al. [26]	Contact ball	A high-accuracy glass scale with a slider	Contact force < 0.3 mN; 0.14-nm scale resolution	Steep optical mould grinding	The variation of probe friction force was reduced by tilted angle configuration.
2	Chen et al. [27]	Contact ball	N.A.	Similar to offline profilometre in terms of form deviation	Aspheric mould grinding	Normal compensation tool path was generated according to the reconstructed profile from OMSM.
3	Zhang et al. [13]	Contact ball	A LVDT sensor with an air bearing slide	20-nm resolution; measurement standard deviation 10 nm	Freeform diamond turning	A novel compensation method is proposed using a combination of on-machine and off-machine measurement.
4	Gao et al. [29]	SPM	AFM head with a robust linear encoder	0.5-nm resolution	Micro-structured surface FTS machining	The use of linear encoder increases the robustness of AFM head and alignment issue was investigated for accurate measurement.
5	Zhu et al. [31] and Zhu et al. [32]	SPM	Position-servo STM with ultra-sharp stylus	5-nm vertical resolution	Fly-cutting and STS machining	A tip-tracking strategy was proposed to extend the measuring ranges. It is capable of scanning steep micro-structured surfaces (V grooves and compound eyes).
6	Chen et al. [35] and Chen et al. [36]	Piezo force sensing	FS-FTS	Sub-mN contact force; 30 nm resolution	Micro-structured surface machining	Defect repair and relay fabrication of micro-lens arrays were achieved with FS-FTS.

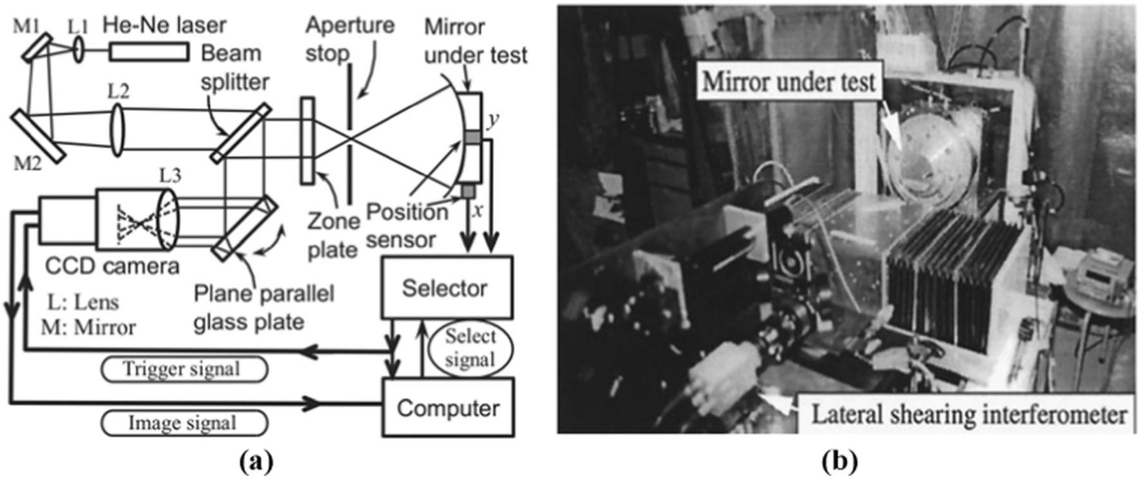


Fig. 12 Schematic (**a**) and experimental setup (**b**) of on-machine shearing interferometre for diamond-turning processes [37]

interferometer for closed-loop control of a piezoelectric translator (PZT), which allows translation of the WSI reference mirror to compensate for the vibration of the measurement samples and stabilise the capturing process. The currently used stylus measurement will be replaced by WSI (as shown in Fig. 19).

Due to the sensitivity to environmental disturbances and complex system configuration of interferometric instruments, non-interferometric OMSM has been also investigated by researchers. Röttinger et al. [45] integrated a miniaturised deflectometry on a Moore diamond-turning machine, which could inspect high-precision specular surfaces without rechucking operations (as shown in Fig. 20). Both global calibration and parasitic reflection reduction were developed to boost the usage of deflectometry. On-machine deflectometry has the advantages of the robustness to environment disturbances and measuring freeform surfaces without extra null testing. By rotating the object with the machine's rotational axis, the field of measurement was easily increased to cover the large aperture and steep mirrors.

Confocal microscopy is an effective tool for surface measurement in the micro-scale. Compared with other optical methods, the maximum detectable slope can be as large as 75° with enough scattered light enhanced by software and hardware [46]. All these characteristics make it applicable to measure complex and high-slope structured surfaces in the manufacturing environment. Zou et al. [47] applied a commercial chromatic confocal tool on an ultra-precision turning lathe for 3D measurement of diamond-turned aspheric surfaces. As shown in Fig. 21, the sensor was mounted perpendicular to the vacuum chuck plane and aligned with a reference sphere. The combined standard uncertainty of the measurement system was estimated to be 83.3 nm, which mainly resulted from the flatness uncertainty of the scanning hydrostatic slide.

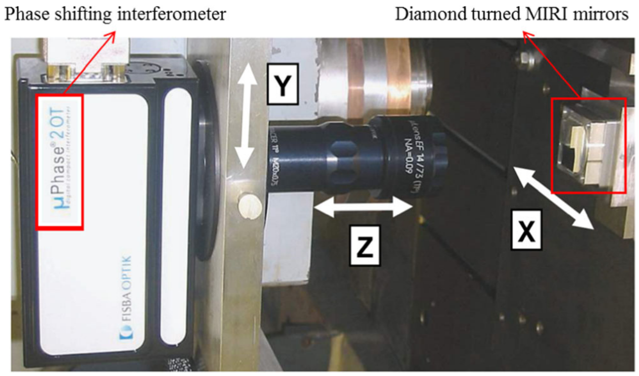


Fig. 13 PSI on-machine measurement of diamond-turned MIRI spectrometer mirror [38]

Commercially available chromatic sensors are also provided as accessories in several commercial ultra-precision machine tools. For example, Niehaus et al. [48] from Schneider GmbH integrated chromatic probing in the commercial ultra-precision machine tool (UPC series). With the sample clamping setup and consistent data exchange format, measurement can be performed immediately after the machining process. In addition, the fully integrated measurement system permits to automate the correction cycle to compensate the form errors. Innolite GmbH [49] developed OMSM solutions consisting of nanometric chromatic non-contact sensors, which are fully integrated into the ultra-precision machine tools and the control system for advanced characterisation. Dimensions, surface form and optical axes can be measured on-machine to drive the manufacturing productivity.

Moreover, several researchers developed special OMSM systems for corresponding applications in order to characterise the functional-related geometric properties. For instance, Gao et al. [50] developed a 2D optical slope sensor with a multi-spot light beam, for on-machine characterisation of local slopes of the FTS-turned sinusoidal surface. As illustrated in Fig. 22, the sensor unit was mounted opposite to the cutting tool on the feeding slide. A cylindrical lens was integrated in the OMSM system and thus the curvature of the cylindrical

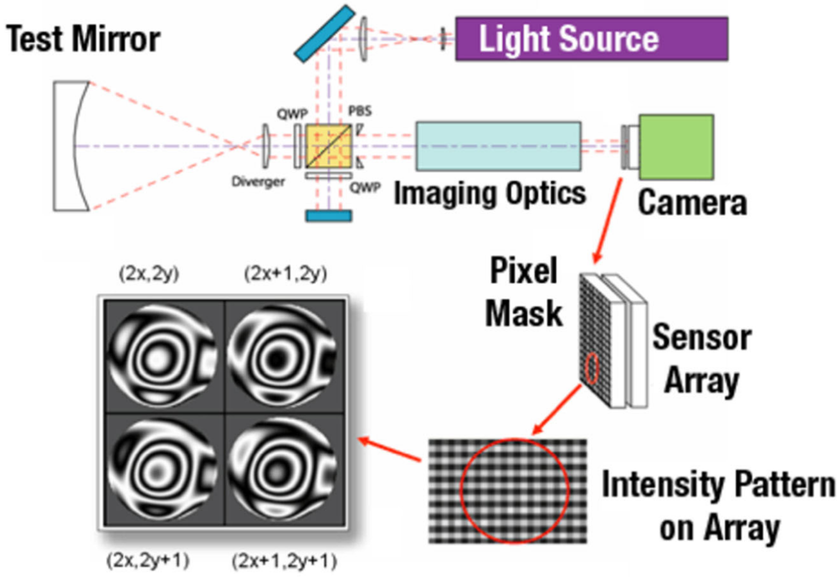


Fig. 14 Principle of the dynamic interferometer [39]

workpiece would not affect the measurement of slopes of the sinusoidal structures. The OMSM enabled the inspection of machining quality without removal of the master drum from the spindle and assisted to effectively reduce surface slope errors.

To overcome the rigorous environmental requirements for on-machine optical measurement system, Li et al. [51] presented an in situ 3D metrology system based on a disparity pattern autostereoscopic (DPA) principle to measure micro-structured surfaces on an ultra-precision machine (shown in Fig. 23). The system adopted a micro-lens array to capture raw 3D information and established a 3D digital model of the target surface to directly extract disparity information. The system setup was simple and compact. Under different measuring environments, fast data acquisition was achieved with high accuracy in 3D computational reconstruction of complex surfaces. Based on statistical analysis, sub-micrometre measurement repeatability was achieved by means of error-elimination process.

Table 2 summarises state-of-the-art researches on non-contact types of OMSM and corresponding applications in ultra-precision machining processes.

3.3 Comparison among different OMSM

To sum up, contact methods have been commonly used for on-machine metrology for its technological maturity. Compared with optical methods, contact methods are applicable to measure high-slope surface geometries. However, the contact methods normally operate at a low scanning speed and the contact nature makes them unsuitable to measure the ultra-smooth and soft surfaces [52]. Some SPMs are also developed for ultra-precision machining applications. However, the tip

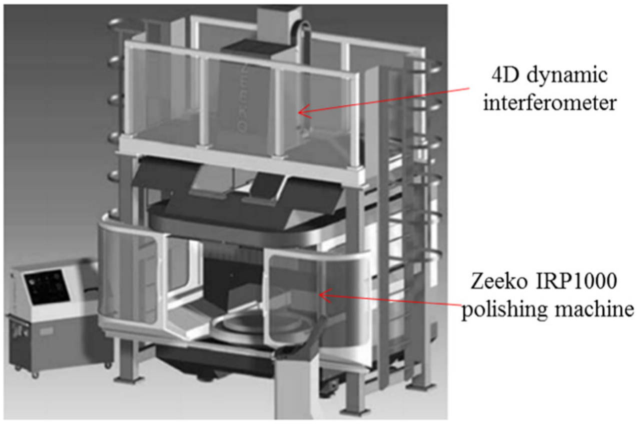


Fig. 15 Large telescope optics polishing system with on-machine dynamic interferometer measurement [40]

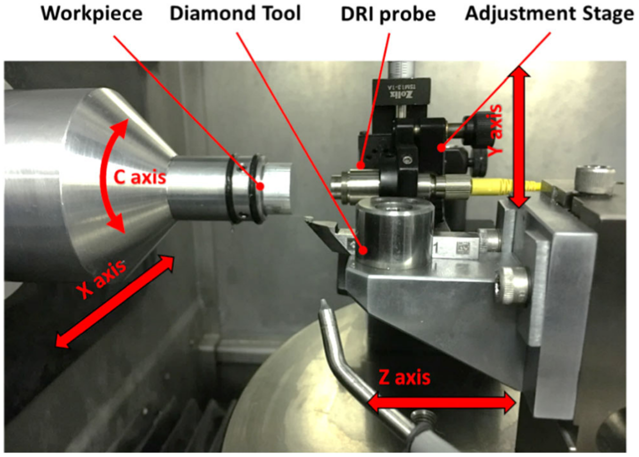


Fig. 16 Single-point DRI integrated on an ultra-precision turning machine [19]

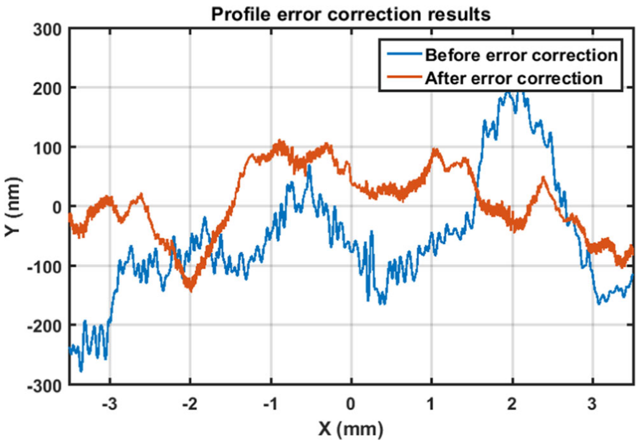


Fig. 17 Profile accuracy improvement after corrective machining with OMSM [42]

wear issue is still a big challenge for large area and long-time measurement.

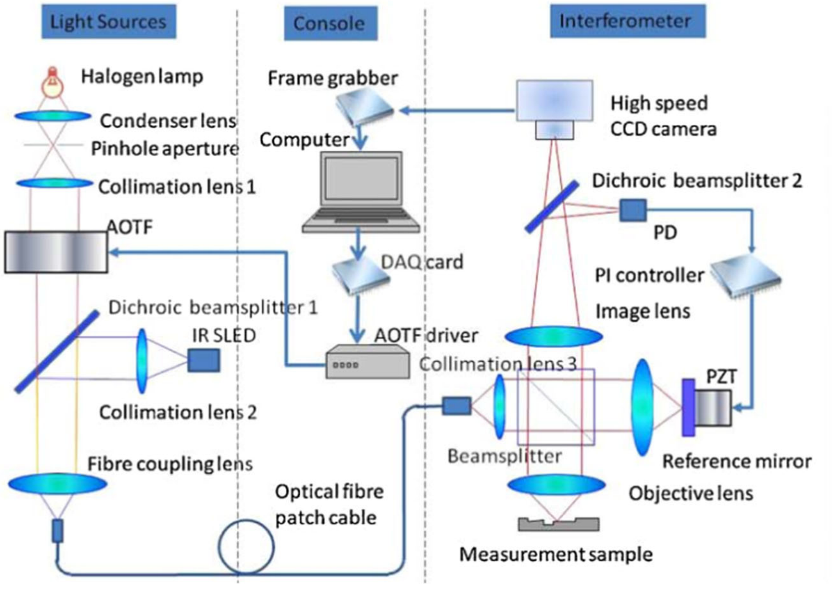
Optical techniques are considered more suitable for measurement on precision manufacturing platforms because of their fast response and non-destructive nature. With the development of calibration and processing algorithms, non-interferometric methods such as deflectometry and confocal sensing are receiving more attention in specific measurement conditions. However, for ultra-precision machining applications, robust interferometry is still the best choice because of its unbeatable measurement resolution (nanometre and even sub-nanometre). According to the discussion above, the merits and limitations of different OMSM types are compared (summarised in Table 3).

From the data acquisition perspective, the OMSM type can be classified into single-point methods and areal methods. Areal methods allow full-field acquisition of surface height data at a static position, while single-point methods need additional scanning mechanism to cover the areal surface. In this sense, areal methods are more efficient for surface measurement compared with single-point methods. However, single-point methods are able to physically separate imaging optics from the interrogation apparatus, which greatly reduces the influence from machine tool environment on the measurement results. The use of fibre-linked objectives in single-point OMSM allows further miniaturisation of the measurement apparatus in the volume-limited machine environment.

4 Challenges and outlook

OMSM will not only allow the assessment of machined surfaces just-in-time, but also provide valuable feedback to the process control. Different types of OMSM have been integrated into the ultra-precision machining processes and proven to improve the measurement efficiency and machining accuracy. Examples have been presented in the field of diamond turning, ultra-precision grinding, polishing, fly cutting, etc. However, there are still several technological gaps to be bridged. With the evolution of autonomous ultra-precision manufacturing, the next generation of OMSM is required to have better performance in terms of high-speed capturing, robustness, low cost, and miniaturisation combined with the same level of measurement precision as state-of-the-art laboratory-based measurement systems [6]. More importantly, machining-metrology integration needs to be performed in a more intelligent manner with the advancement of artificial intelligence, modelling and sensing techniques. The main challenges and

Fig. 18 Schematic diagram of WSI with vibration compensation [44]



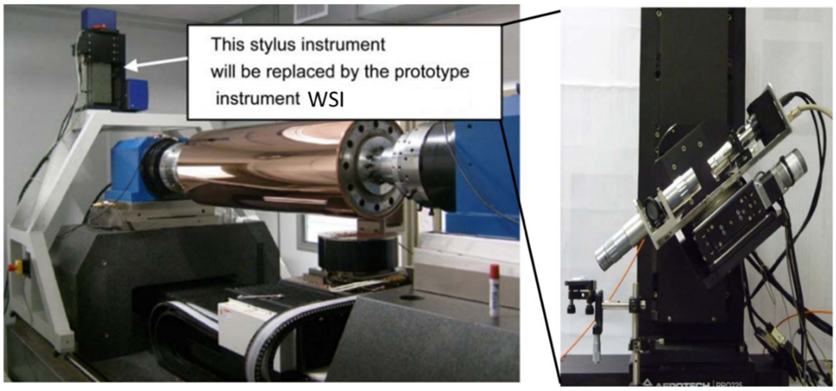


Fig. 19 WSI for on-machine topography measurement [43]

outlook of machining-metrology integration in industrial and academic interest are discussed as follows.

- To achieve successful machining-metrology integration, machining process should be comprehensively understood beforehand. Surface generation modelling provides an important means for the investigation of ultra-precision machining process. Although several geometric models have been established in this field, research of some physical mechanisms in material removal are still in the early stage [53]. The actual surface generation is very complex, which is affected by numerous factors such as cutting forces, machine tool dynamics and sample material properties. A more comprehensive model will contribute to further understanding the cutting mechanism as well as more accurate prediction of surface generation. Furthermore, the knowledge acquired through the modelling of machining process provides valuable priori information to the integrated measurement process, which is potential to increase the inspection efficiency and intelligence.
- Advanced and emerging products such as retro-reflective prism films and structured drum rollers have large-scale (up to metres) form and fine components with complex structures (nanometre tolerance). When large area surfaces need to be measured with ultra-high resolution, efficient sampling must be applied to reduce the measurement data overhead [54]. Moreover, the conventional uniform sampling strategy may lead to undesirable results, including over-sampling data points on low curvature regions of the surface, or under-sampling on strong features and high curvature regions. Integration of OMSM preserves the datum consistency between measurement and machining process. Adaptive and intelligent sampling techniques are of promise in the further improvement of OMSM efficiency while ensuring the accuracy as well.
- Due to the environment in the machine tools, metrology characteristics of surface measurement instruments would deviate from those tested in laboratories. Calibration of OMSM system is necessary and the systematic errors need to be compensated before the inspection process. For ease of use in practice and promotion of OMSM application, simple and fast calibration schemes need to be investigated. It is preferred that influential factors (such as machine-induced vibration, kinematic errors, probing slope and linearity errors) are calibrated all together (using a single standard artefact with designed features) rather than separately. Also, OMSM developers are suggested to work closely with machine tool manufacturers to share the calibration scheme and data for compensation, which will enhance the calibration efficiency and fidelity. In addition, the robustness of OMSM instrument will be further

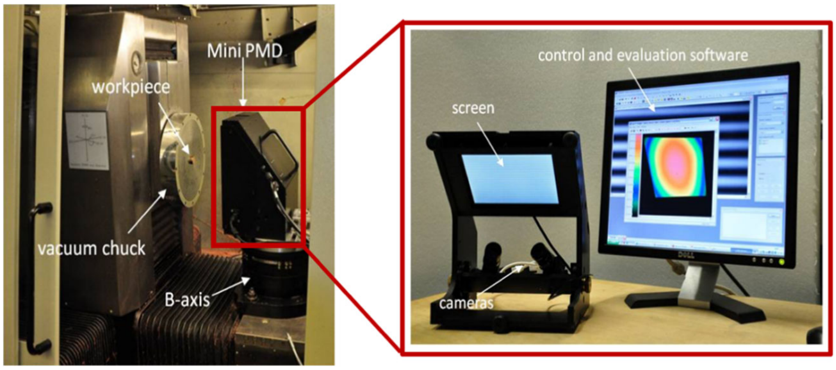


Fig. 20 Integration of mini-PMD on a multi-axis ultra-precision machine tool [45]

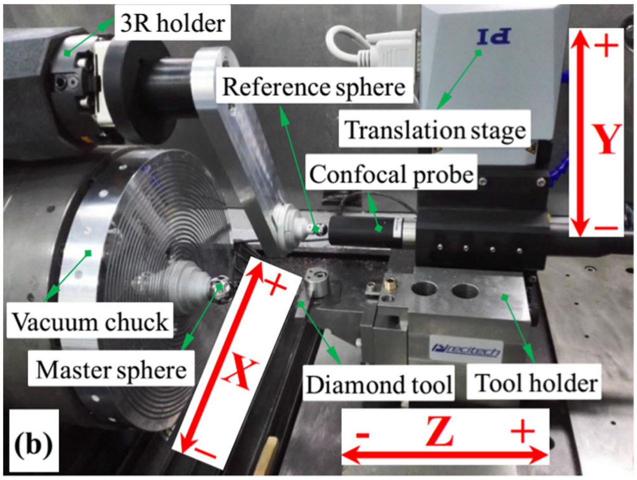


Fig. 21 Chromatic confocal–based on-machine measurement for ultra-precision turning processes [47]

enhanced with system miniaturisation and developed calibration algorithm.

- Due to demanding tolerance in ultra-precision manufacturing, deterministic surface measurement is imperative. With the lack of remounting errors, OMSM will aid to establish a deterministic model between the machining parameters and the surface deviation. With OMSM automation and a large amount of captured data, artificial intelligence methods (such as fuzzy logic and neural network) and advanced optimisation methods (such as genetic algorithm, particle swarm optimisation and ant colony optimisation) can be investigated to optimise the ultra-precision machining processes. Artificial intelligence models take into consideration the particularities of the equipment used and the real machining phenomena. OMSM together with artificial intelligence is considered

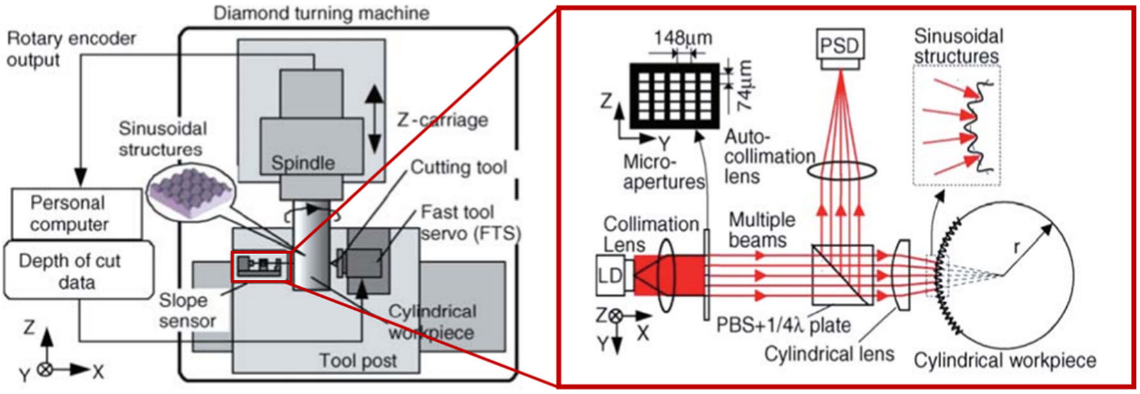


Fig. 22 Optical slope sensor for on-machine measurement of FTS machined sinusoidal structures [50]

Fig. 23 Disparity pattern-based autostereoscopic system for in situ inspection of diamond-turned micro-structures [51]

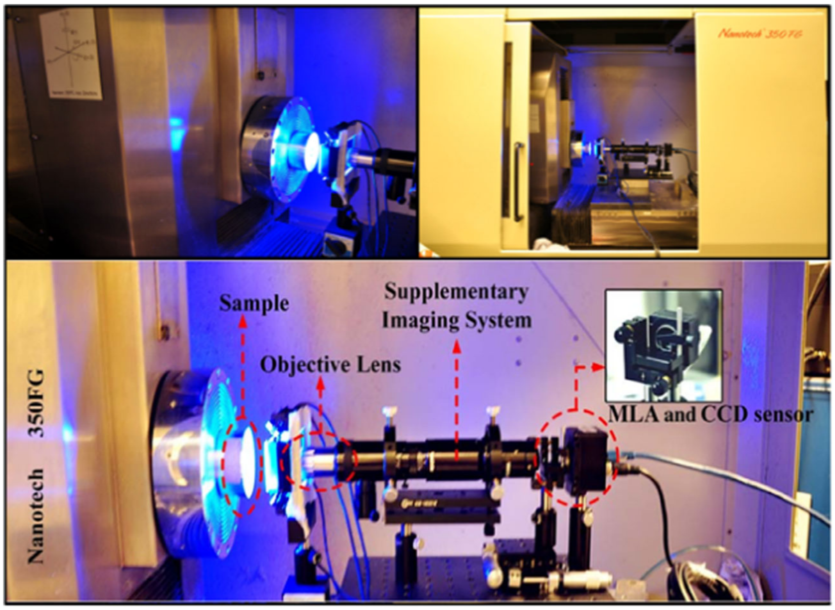


Table 2 Non-contact optical type of OMSM and application

No	Author/year	Principle	Instrument	Performance	Application	Remarks
1	Shore et al. [38]	Interferometry	Trioptics μ phase PSI	1.9 nm repeatability	MIRI mirror diamond turning	Relative locations of confocal positions are evaluated with the aid of OMSM
2	Nomura et al. [37]	Interferometry	Lateral-shearing interferometer	Good agreement with results measured by Fizeau-type interferometer	Diamond turning	Interference fringes during measurement were less affected by mechanical vibrations and air turbulence in the optical paths
3	King et al. [40]	Interferometry	4D dynamics interferometry	30 μsec acquisition time; 0.002λ wavelength precision	Large-scale optics polishing	Single-shot and vibration insensitive measurement
4	Li et al. [19]	Interferometry	Single-point DRI	High-dynamic measurement with nanometre resolution and millimetre vertical range	Freeform/structured surface diamond machining	Optical fibre–based DRI assists the deterministic process investigation and corrective machining
5	X. Jiang [43]	Interferometry	Wavelength scanning interferometer	15-nm vertical resolution; anti-vibration < 300 Hz	Micro-structures diamond turning on drum rolls	Real-time vibration compensation with a monitoring interferometer
6	Röttinger et al. [45]	Deflectometry	mini-PMD	Sub-micron accuracy	Freeform ultra-precision machining	Environmentally insensitive and able to measure arbitrary freeform without null testing
7	Zou et al. [47]	Chromatic confocal	STIL confocal point sensor	Relative measurement error 0.022%; combined standard uncertainty 83.3 nm	Diamond turning	Measurement uncertainty mainly resulted from the flatness of the scanning slide
8	Gao et al. [50]	Auto-collimation	Optical slope sensor with a cylinder lens	N.A.	Cylindrical sinusoidal structures FTS machining	The surface slope errors caused by the tool nose geometry were corrected with the integrated slope sensor.
8	Li et al. [51]	Auto-stereoscopy	Disparity pattern-based auto-stereoscopic 3D system	Sub-micrometre measuring repeatability	Pyramid structured surfaces machining	Compact, fast capturing and environmental robust

Table 3 Merits and limitations of different types of OMSM

Measurement nature	OMSM type	Merits	Limitations
Contact	Probing ball	Ease of integration, technical maturity	Slow scanning, damage on the soft surfaces, limited lateral resolution
	SPM	Nanometric resolution	Slow scanning, tip wear, limited vertical range
Non-contact optical	Interferometry	Nanometric (or sub-nanometric) resolution and fast acquisition	Vulnerable to environmental disturbances, slope limitation
	Deflectometry	Arbitrary shape measurement and simple setup	Limited global accuracy and complex calibration processes
	Confocal	High-measurement angle	Limited measurement precision

the key to achieving autonomous ultra-precision manufacturing.

- With the theoretical and experimental knowledge acquired by physical modelling, OMSM is shifting from general geometry-oriented sensing to specific function-oriented sensing. Function-oriented OMSM can directly inspect and verify the surface functional behaviour. Research work is suggested to study the relationship between the functional performance and surface geometric accuracy, which provides an important means for selection of the OMSM measurements and optimisation of re-machining processes.

The field of OMSM and metrology-integrated manufacturing will continue to be innovative and of great interest in the next decade. More potential applications associated with OMSM will be explored to exploit the integration benefits for further enhancement of the ultra-precision manufacturing performance and intelligence.

5 Conclusions

The OMSM and associated application is essential to enhance ultra-precision manufacturing, which facilitates the direct assessment of machined surfaces and provides timely feedback to the process control for further optimisation and post-process correction. However, there are several technological considerations, including the requirement of OMSM instrument and integration issues in machine tools.

This paper has reviewed the state-of-the-art OMSM and corresponding applications in ultra-precision machining processes. The merits and limitations of different OMSM types have been analysed. The contact methods are limited by low-speed capturing, possible damage to the delicate machined surface and the long-term tip wear. Non-contact optical types are preferred for their non-destructive nature and fast acquisition. Particularly for ultra-precision machining applications, robust interferometry is considered the best choice for its unbeatable measurement precision. Areal OMSM is efficient as it allows full-field acquisition of surface height data, while single-point method is preferred due to the ability of miniature fibre probes to relay distance and surface information to remote interrogation apparatus. Future development of machining-metrology integration is suggested to include (but not limited to): (1) the establishment of comprehensive machining model as priori information for OMSM; (2) intelligent sampling and characterisation techniques; (3) robust design and fast calibration of OMSM; (4) autonomous process optimisation with metrology and artificial intelligence; and (5) function-oriented OMSM.

Advanced OMSM for ultra-precision machining is in its infancy but will continue to be of great interest for both academia and industry. With the development of artificial intelligence, modelling and sensing techniques, benefits of metrology integration will be further exploited to improve the performance and intelligence of ultra-precision manufacturing.

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