On-Machine Measurement System and Its Application in Ultra-Precision Manufacturing

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Abstract

The increasing complexity of functional surface structures in terms of structure size and area shape and scale brings considerable challenges on the existing ultra-precision manufacturing and surface measurement technologies. The discrete nature of manufacturing cycle in industry where the measurement instrument used for quality assessment is normally in an offline manner significantly limits productivity and flexibility.

This chapter gives a brief coverage to the historical development of surface metrology and measurement systems embedded within the manufacturing process. The current typical metrological techniques and instrumentation for carrying out embedded surface metrology are presented from the aspects of working principle, advantages, applications, and limitations. The specific emphasis has been put on the applications of embedded measurement system in ultra-precision manufacturing environment. It is found that with embedded metrology, it is possible to further improve the processing efficiency and reliability of high-precision manufacturing. The merits and limitations of embedded measurement systems used in ultra-precision manufacturing are compared and discussed.

Keywords

On-machine measurement · Surface functionality · Ultra-precision manufacturing · Surface measurment · Embedded metrology

Introduction

Freeform and micro-/nanostructured functional surfaces have been widely used in astronomy, aerospace, automotive, semiconductors, telecommunicating, IT facilities, and medical and foods safety, changing our lives in terms of increased living standards. To ensure the designed functionality, it normally requires surfaces to have sub-micrometer form of accuracy and nanometer surface topography (Jiang and Whitehouse 2012). Diamond machining including diamond turning, high-speed micro milling, fast tool servo, slow tool servo, and fly cutting plays a key role in the fabrication of functional structured surfaces with mirror finishes. However, the increasing complexity of surface structures in terms of scale (both the structure size and the area of structured surface) and shape of the products (e.g., sphere, aspheric, freeform) impose considerable challenges on the existing ultra-precision fabrication and surface measurement technologies. The measurement systems used for product quality assessment in industry are usually in an offline manner where the samples are measured within the field of view of the instrument. The discrete nature of production cycle limits the further development of productivity while allowing high reliability and flexibility.

Indeed, in many high-precision applications, the removal and remounting of workpieces in post-process metrology would cause unavoidable alignment error if re-machining processes need to be carried out. For example, the polishing of large telescope optics (Walker et al. 2006) and the mounting of the sample on a fixed measurement platform are very challenging and even impossible when the sample dimensional size exceeds the measurement scale of current measurement equipment having nanometer form resolution. The movement of components from manufacturing environment to measurement instruments also increases production cycle times and component cost. The integration of metrology into manufacturing environment will preserve the consistency between the machining and measurement coordinates and thus allows further improvement of machining accuracy and efficiency by eliminating repositioning operations.

Additionally, for some demanding advanced production line such as the manufacture of flexible photovoltaics (PV), printable electronics, structured films, and other roll-to-roll (R2R) manufacturing processes (Elrawemi et al. 2015), offline or post-process measurement is not applicable anymore. The high throughput of the manufacturing processes means that detection of defects post-manufacture would result in the wastage of a large quantity of products. Although the existing machine-vision inspection solutions can help detect surface defects, it is incapable to provide height information for the characterization of all defects. Thus, it is imperative to shift the approach of metrology from offline lab-based solutions to embedded measurement in manufacturing platforms (Jiang and Whitehouse 2012). With embedded metrology it is possible to enhance the material processing and reliability of high added-value critical components, ultimately leading to cost-effectively eco-manufacturing.

This chapter will briefly introduce the historical development of surface metrology and measurement systems and highlight the requirements for embedded measurement used in manufacturing process. Typical metrological techniques and instrumentation for embedded surface metrology are introduced from the aspects of working principles, advantages, and typical applications in ultra-precision manufacturing as well as their limitations.

Surface Metrology

Definition of Surface Metrology

Surface metrology refers to the measurement that describes the surface deviation between a structured surface and its ideal shape (Whitehouse 2004). Surface metrology is used in engineering to understand the creation and behavior of surface topographies. It specifically covers measurements such as surface texture, surface roughness, surface shape, surface finish, form, etc.

The surfaces are generally manufactured to provide specially designed functional properties. These surfaces are produced by variety of processes such as diamond turning, milling, grinding, polishing, molding, etc. High-precision engineered surfaces of desired functionality are usually manufactured by manipulating geometrical features on surfaces. Functional properties directly relate to the geometrical features, and hence measurements of such features are extremely important. The measurement results also give valuable feedback to manufacturing units for controlled manufacturing.

Surface Features and Characterization

Surface features are generally characterized along the vertical direction by height parameters and along the horizontal direction by spatial (wavelength) parameters. The structures on the surfaces are basically various components of frequency related to the manufacturing process or the production technique used. According to the spatial frequency, a surface profile can be generally divided into three types of surface features, namely, roughness, waviness, and form.

Roughness refers to the highest-frequency components present on a surface of interest. Roughness depends on the type of manufacturing method employed rather than the machine type.

Waviness results due machine deflections and vibration and is defined as repeating irregularities with spacing greater than roughness. In terms of frequency, the next lower order frequency components on the surface represents waviness.

Form error is the overall parameter describing the maximum of the local deviations of the real form of a line or surface from the nominal – geometrically ideal feature. Form error is generated due to lack of rigidity of the workpiece during the machining process allowing it to flex or bend. This contains lowest frequency components on a surface. Several factors such as material strain, temperature changes during machining, and excessive surface residual stress can cause form error.

With the development of novel and robust mathematical tools, the characterization interest has shifted from profile to areal, from stochastic to tessellated, and from simple geometries to complex freeform surfaces. For areal surface characterization, the concept of scale-limited surface has been developed. The scale-limited surface contains S-F surface and S-L surface, which are created by a combination of S-filter, L-filter, and F-operator as shown in Fig. 1 (ISO Standard 25178-2 2012).

Procedures of Surface Measurement

Surface measurement involves three basic steps: acquisition of data by an instrument, filtration, and analysis by parameterization (Fig. 2). Sometimes fitting of the acquired data is required to remove any underlying shape due to the tilt of sample relative to the measuring instrument. Filtering is used either to remove the undesired aspects of surface topography or to select the elements which are needed for analysis or evaluation. So, filtering wherever employed must be carried out with utmost care so that the desired information always remains. After filtering the

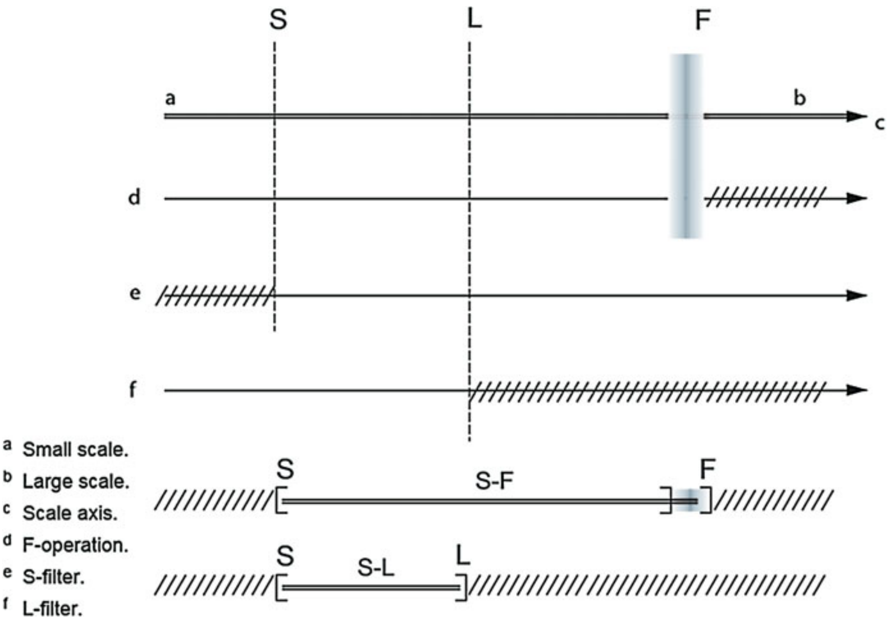


Fig. 1 Relationships between the S-filter, L-filter, F-operation, and S-F and S-L surfaces (ISO Standard 25178-2 2012). **S-filter**, which defined as a filter that removes small-scale lateral components from the surface resulting in the primary surface. **L-filter**, which is used to remove large-scale lateral components from the primary surface or S-F surface. **F-operator**, which removes the form from the primary surface. An S-F surface results from the use of an S-filter and an F-operator in combination on a surface and an S-L surface by the use of an L-filter on an S-F surface

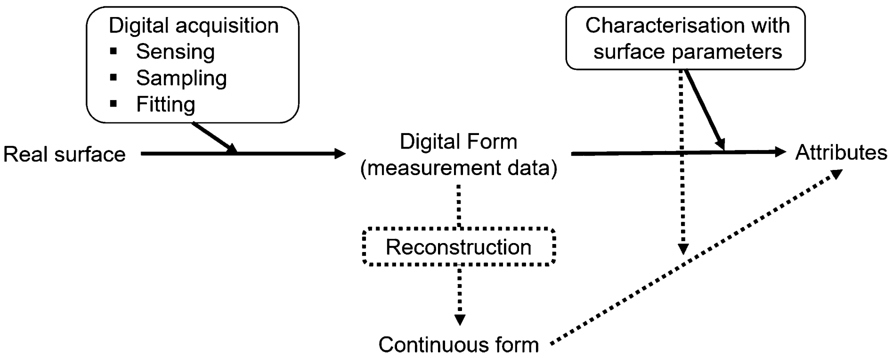


Fig. 2 General procedures for the measurement of a patch of surface topography

data is analyzed to describe the surface features in some numbers called parameterization.

Large numbers of surface parameters are developed to characterize the surface topography. These surface parameters have been categorized into mainly four groups: height parameter, shape parameter, wavelength parameter, and combination of these known as hybrid parameter. Similarly, statistical function gives detailed statistical description of surface properties. Examples of statistical functions are the power spectral density function, the autocorrelation function, the amplitude density function, and the bearing area curve.

Measurement Systems Used in Manufacturing Process

Structured surfaces have enabled functional advancements such as lubrication, adhesion, wear diagnostics, friction, and so on. As the dimensions of products are getting smaller, the surface features and its properties become a dominant factor affecting the functionality of products. With advanced surface metrology techniques, there is high possibility of improving material processing processes, making manufacturing more efficient, reliable, economic, and less environmentally sensitive.

Classification of Optical Measurement Systems

Many reviews have been written regarding various optical methods, offering a detailed list of categories such as polarization interferometry, speckle interferometry, heterodyne interferometry, white-light interferometry, moiré and structured light methods, holographic methods, confocal microscopy, optical scattering, focus variation, etc. All these categories can be divided into two types, namely, non-interferometric and interferometric techniques. The surface characterization can be performed at different conditions according to requirements of applications. Vacharanukul and Mekid provided a classification for the act of measurement during the manufacturing process in three groups, namely, in- process, in situ, and post-process (Vacharanukul and Mekid 2005).

In-process or in-line metrology can be defined as any measurement method which occurs while the manufacturing process continues. This may include use of the metrology as part of a control system to provide real-time feedback information for compensation of manufacturing errors or later in the manufacturing chain for continuous processes. The harsh factory environment brings big challenges for in-process measurement. The in-process metrology system should be robust enough to allow the motion of the measurand, vibration, and heat generation. The system should also be protected from manufacturing contaminants such as swarf, dust, and cooling fluids. Examples of in-process metrology include the measurement of moving webs in a roll-to-roll manufacturing line as well as the measurement of conveyed products.

On-machine, in situ, online, or embedded metrology is the process of measuring surfaces without removal of the workpiece from the manufacturing platform. The manufacturing is actually halted during the measurement process. Typical examples of on-machine metrology like grinding tool wear measurement, characterization of tip geometry of milling cutters, measurement of both the molds, components in precision injection molding, measurement of surface roughness, form deviation of freeform surfaces produced by diamond machining, etc. Compared to in-process measurement, it not only significantly relaxes the challenges for implementation due to a mild assessment surroundings but also takes the advantages of not having to remove/refit workpiece in terms of further surface modification. Challenges faced are those such as machining platform motion errors, environmental disturbances, and process contaminants.

Post-process or offline metrology describes the measurement through instruments located remotely from the manufacturing process. The maturity of measurement technologies and the ability to perform measurement at a specific temperature, humidity, pressure, as well as anti-vibration environment are advantages of office metrology. However, the discrete nature between production and measurement, the cost of upkeep of a separate facility, as well as the operator costs of nonautomated metrology are significant drawbacks of using offline metrology. It is also time consuming to fix and realign the workpiece on a machine tool for further surface modification.

Advantages of Embedded On-Machine Surface Metrology

Compared with offline surface measurement, the following benefits of on-machine measurement are offered:

(A) Increased inspection efficiency

From the production perspective, the integration of measurement system in manufacturing environment increases the inspection efficiency and production throughput and reduces the cost associated with transportation labor and tools, staff training, and maintenance of offline measurement equipment.

(B) Improvement of machining accuracy

The coordinate system between machining and measurement process is consistent through the whole manufacturing process when machining with assist of on-machine measurement system. This is particularly important when machining ultra-precision surfaces requiring sub-micrometer and even nanometer level form tolerance.

(C) Improvement of automation level

The automated nature of on-machine metrology makes it indispensable for autonomous and intelligent manufacturing. The machined surface can be inspected in situ, and the extracted information can be promptly fed back to machine control system for product quality control. The intimate knowledge of measurement strategy and other operation experiences can be integrated into CNC machine control system, which means that operator experience is less necessary in the product manufacturing.

Requirements for Embedded Metrology System

In general, the embedded system used in manufacturing platform need to be compact and flexible enough to allow for an easy installation. Furthermore, they must be capable of reaching the same performance as their commercial standalone equivalents (Jiang and Whitehouse 2012). In order to match and exceed the performance of offline metrology tools, the selected embedded measurement instrument must meet as many of the following requirements as achievable:

- **Robust to environment**. The effects of temperature, humidity, vibration, and atmospheric pressure and the presence of lubricants/contaminants must not adversely affect the quality of measurement.
- **Compact design**. The instrument is supposed to be compact enough to be integrated into a machine.
- **Measurement rate**. The measurement rate/speed of the instrument should match the production line requirement. High measurement rate will help reduce the effects of environmental noise on measurement results and save the time for a complete measurement.
- **Measurement range**. The measurement range of the instrument should be large enough to cover all the features of interest.
- **Dynamic range**. The ratio of axial range to resolution is important to (a) increase the instrument versatility in measurement and (b) reduce the cost associated with the requirement for many probes/objectives to cover a range of measurement regimes.
- **Measurement precision**. The measurement precision of embedded metrology system must equal or exceed existing offline methods due to the ever-decreasing feature sizes of engineered surfaces.

Typical Embedded Measurement Systems

In general, an appropriate measurement technique used for a surface metrology should be determined according to the function of the surface and its applications. In this section, typical embedded measurement systems are selected and briefly introduced from the aspects of working principle, typical applications, advantages, and limitations.

Contact Profilometer

Stylus profilometry (Fig. 3) and scanning probe microscopes (SPMs, Fig. 4) are two typical contact profilometers. A tactile probe is used in contact profilometer to collect the surface topography information. The stylus-based profilometer traces a contacting stylus through a transducer (acting as a gauge) and measures the vertical variation of the stylus

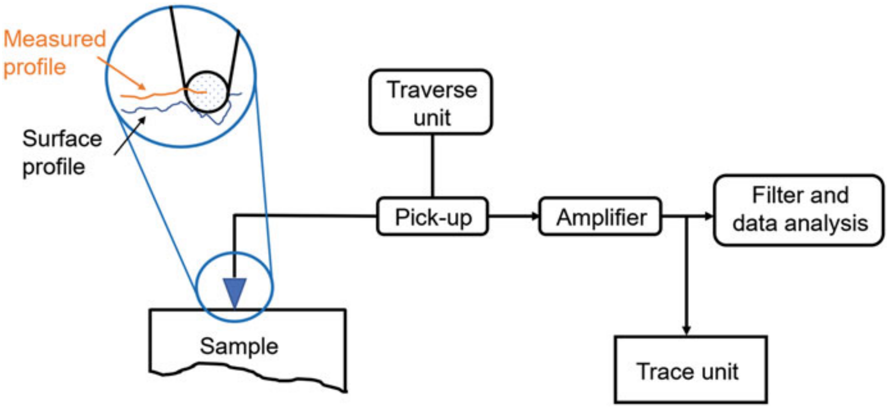


Fig. 3 Schematic representation of stylus profilometer

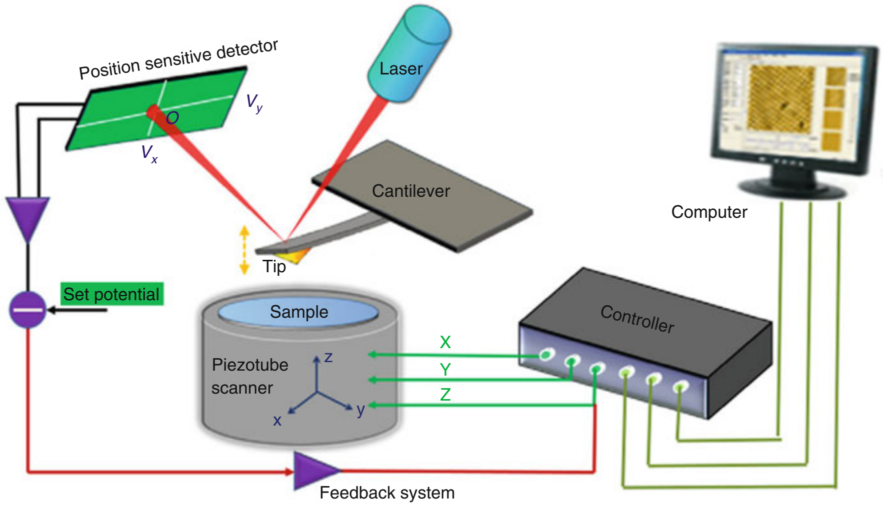


Fig. 4 Schematic diagram of the basic working principle of AFM (Guo et al. 2013)

as it traverses across the surface of interest. The lateral resolution is determined by the radius of curvature of stylus tip and the slopes of the surface irregularities. Currently the measurement range can achieve up to several millimeters in height with a vertical resolution in nanoscale. Equipped with an extra translational stage, a stylus profilometer is able to measure areal surfaces in a raster scanning mode. Many commercial products have been developed by the Taylor Hobson Limited, typically Talysurf PGI (surface form measurement) and Talyrond series (roundness measurement).

SPMs are developed based on the scanning tunneling microscope (STM) and the atomic force microscope (AFM). It has much common with the stylus-based instrument but uses STM/AFM fine level tips to scan surfaces. The surface information collected by STM/AFM is the charge density or atomic forces, not the height data.

The contact profilometer is preferred for measurement of large deviation freeform surfaces due to its high lateral/vertical resolution and large measurable range. However, the contact stylus tips have high risk to be damaged in harsh measurement environment. It is also not suitable to measure soft and dedicate surfaces as the surface would get scratched or even functionally damaged when the stylus tip scanning the surface. The finite size of stylus tip also makes it impossible to penetrate into all valleys of the true surface and thus introduces a nonlinear distortion to the measured envelope. The image resolution is highly dependent on the tip geometry, and the point-by-point scanning of contact profile meter also makes the measurement of surface topography time-consuming. From these point of views, contact profilometers are usually considered not applicable to the metrology in manufacturing environment. However, several attempts have been conducted recently to use scanning probe microscopes (SPMs) with finer tips to realize the on-machine measurement of ultra-precision machined microstructures. More details are introduced in the following section.

Machine Version

Machine vision is imaging-based optical metrological system which is commonly used for surface inspection in industry such as die attach bond inspection, ball grid array inspection, solar and PV device inspection, metal surface inspection, print inspection, etc. As shown in Fig. 5, it consists of four main parts, namely, illumination system, imaging optical system, detector, and computer system. The tested surface is illuminated by a light source, and then the features within the field of view (FOV) are imaged by a high-speed camera. The recorded grayscale images are analyzed by data processes algorithms such as averaging and filtering to characterize the surface features of interest. The selection of illumination source depends on the applications. Bright field transmission illumination is normally used for transparent or nearly transparent material, while dark field illumination system is preferred for glossy surfaces. For low-contrast surface, a diffuse illumination is recommended, and directional lighting source is usually applied for structured surface (Harding 2013). The selection of high-speed camera is normally depended on the requirement of web speed and the minimum feature size on the tested surface. The commercial CMOS cameras usually can offer line rates up to 140 KHz with 4 K pixels and 10 μm pixel size. However, the technique can only provide 2D surface information, and it remains very difficult to obtain the depth information of the tested surface.

Confocal Chromatic Microscopy

Confocal chromatic microscopy (CCM), also known as confocal chromatic sensing (CCS) and confocal chromatic spectrometry (CCS), takes advantage of using two

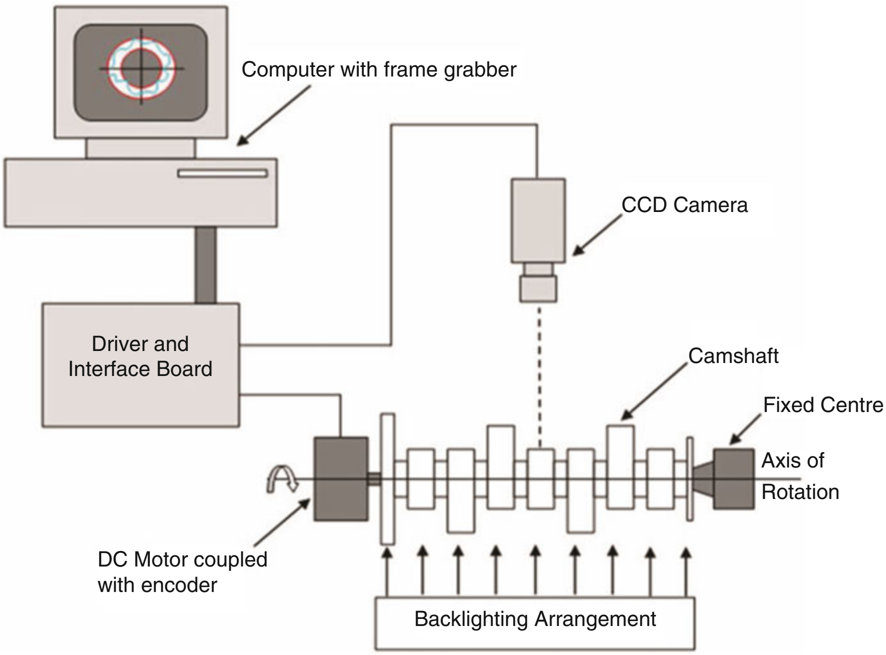
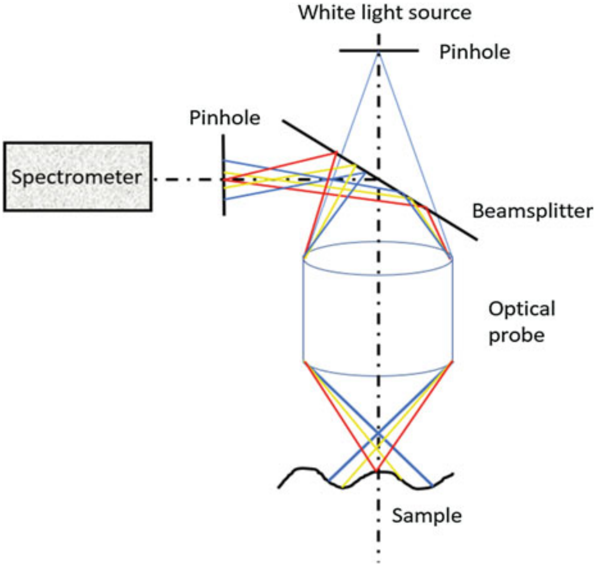


Fig. 5 Configurations for in-line inspection calibration and in situ roundness measurement (Ayub et al. 2014)

pinhole apertures as spatial filters for focused rays (as schematically shown in Fig. 6). Monochromatic or white-light source travels through one pinhole and converges on the sample surface. The other pinhole works as a filter in front of the detector which only allows the reflected focused rays to transmit through it and reached the detector or a spectrometer. Mechanical vertical scanning is required for monochromatic confocal microscopy to get the height information of a point. CCM of white-light source takes advantage of the chromatic aberration introduced by a lens and the range of focal lengths of a broadband light source. Each wavelength of the illumination corresponds to a focal plane along the optical axis. After calibration of the instrument, a range of focal lengths can be used to achieve parallelization scanning in depth direction (Ruprecht et al. 2004). In order to reconstruct surface topography, scanning the surface in XY plane is required.

The confocal microscopy can be potentially applied in in-process metrology due to its compact system design, high measurement rate, and data processing speed. Most recently, company such as Precitec, Nanofocus, and Micro-Epsilon can supply CCM instrument with different performance. However, the confocal microscopy still suffers from the same problems as other microscopy instruments – physical limitation of objective. The vertical measurement range and lateral resolution are largely restricted by the working distance and diffraction limit of objective used if not camera limited (Leach and Sherlock 2013). Another problem

Fig. 6 Schemas of confocal microscopy



with CCM is the occurrence of self-imaging when measuring surfaces with curved profiles such as lens arrays, curved trenches, and grooves with radii (Lyda et al. 2012). The local radius of the surface refocuses wavelengths of the source light that should be out of focus at the measured surface. These refocused lights will travel back into the measurement apparatus and result in a false reading of the surface height.

Optical Interferometry

In the past decades, many interferometry-based metrology instruments have been developed to achieve high measurement accuracy. Optical interferometry is based on the analysis of the fringes generated by two light beams with the same frequency. The beams originate from the same source but traveling along different paths. An optical objective is required to bring two or more beams to interfere. According to the way to split the beam into reference and measurement beams, the interferometric objective can be broadly classified into four types, namely, Linnik, Michelson, Mirau, and Fizeau. The most popular interferometers are phase-shifting interferometry (PSI), white-light interferometry (WLI), and wavelength scanning interferometry (WSI). Interference signal is obtained by varying the path length between the test object and the reference beams. The path length variation is generally induced by either vertical scanning or phase-shifting techniques which involve mechanical scanning. It can also be induced by nonmechanical means such as wavelength scanning and dispersive methods. Vertical resolution of nanoscale level can be achieved by the interference signal, while the lateral resolution is limited by the objectives used.

Phase-Shifting Interferometry

Phase-shifting interferometry (PSI), also known as temporal phase measurement, makes the use of phase changes occurring in an interferogram during a controlled phase shift. These phase change can be induced by rotating polarizers, moving diffraction gratings, translation of mirrors, or tilt of glass slides. The 3-point, 4-point, and 5-point algorithms are commonly used to calculate the interferogram phase. Higher frame number algorithms usually have higher resistance to errors at the expense of measurement rate. Other algorithms such as the Carré algorithm allow calculation of interferogram phase without application of a known phase shift, assuming that the applied phase shifts are equal each time.

The PSI with a single-wavelength light source with long coherence length offers outstanding axial resolution. It is renowned as having sub-nanometer resolution with an achievable repeatability of less than 1 nm independent of field size (Leach 2011). However, the high axial resolution of temporal PSI is offset by its measurement rate. The measurement rate is reduced proportional to the number of camera-captured frames required by the chosen PSI algorithm. This limitation makes PSI particularly susceptible to environmental influence, for example, the vibration, where changes in surface position between frames result in measurement errors.

Another limitation of temporal PSI is the fatigue and failure associated with the translation and mechanical settling of heavy optics thousands of times throughout the life cycle time of the instrument. The relative nature of PSI also results in the phenomenon that the measured surface height wraps around every time the surface height deviates by half the illuminating wavelength or more. The PSI is thus recommended to measure smooth surfaces or step heights less than a quarter of a wavelength.

In contrast to the temporal PSI, the spatial phase-shifting interferometry also known as instantaneous interferometry is an optical measurement method where the required phase shifts occur instantaneously in time. The phase shift of spatial PSI can be induced by polarization of measurement and reference beams and use of multiple detectors. As compared to temporal PSI, the instantaneous nature of spatial PSI can inherently increase the measurement rate by elimination of the requirement for multiple camera frames per measurement. It also avoids the difficulties associated with temporal PSI such as vibration and sample movement. However, the difficulties in calibrating multiple image sensors and the measurement errors introduced by the non-common path nature of spatial PSI are the inherent limitations of the spatial PSI.

A variation of spatial PSI, namely, a single-shot phase-shifting interferometer, has been developed to circumvent the problems suffered by previous traditional PSI. It produces four phases shifted interferograms through use of a quarter wave plate and a pixelated birefringent mask in front of a single detector (Millerd et al. 2006) (Fig. 7). The single-shot nature and much improved measurement rate allow areal measurement of surfaces without sensitivity to vibration or air flow through interferometer paths, making this method potentially advantageous for on-machine measurement of moving films, webs, and other continuous production processes. Zeeko has used this kind of metrology instruments (commercialized by 4D Technology) as part of their on-machine stitching interferometer (OMSI) module for

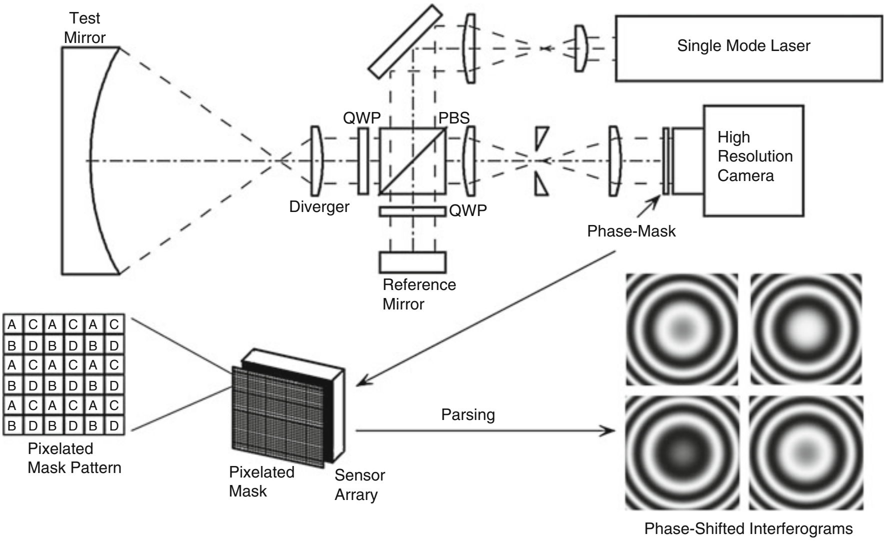


Fig. 7 Twyman-Green configuration for pixelated interferometer (Millerd et al. 2006). It produces four phases shifted interferograms through use of a quarter wave plate and a pixelated birefringent mask in front of a single detector (Millerd et al. 2006) (Fig. 7).

seven axis precision polishing and grinding machines. Nevertheless, dynamic interferometry is limited to near-perpendicular measurement of surfaces and still suffers from the phase ambiguity problem which is common to all phase-shifting techniques (Williamson 2016) (Fig. 7).

Vertical Scanning Interferometry

Vertical scanning interferometry (VSI), also known as white-light interferometry (WLI) or coherence correlation interferometry (CCI), uses the short-coherence length of a wide bandwidth source (typically several hundred nanometers bandwidth) along with the fact that the interference fringes have highest contrast when the path lengths of the interferometer arms are matched. By mechanically varying the length of one arm of the interferometer, the intensity of the interferogram at each pixel is modulated, and a pixel-wise intensity pattern of the surface is generated. The absolute distance of tested surface with respect to reference plane is determined by retrieving the locations of coherence peaks from the captured interferograms. Surface topography is acquired after tracking all coherence peaks within the field of view of the interferometric objective (as shown in Fig. 8).

The absolute (as opposed to relative) nature of coherence scanning methods allows the metrological application to rough surfaces and structured surfaces with large discontinuities. Its vertical measurable range is dependent on the working distance of the objective and the scanning range of the translation system, usually a few micrometers to a few centimeters. Many commercial products using VSI technique have been developed, such as Talysurf CCI 6000 from the Taylor Hobson

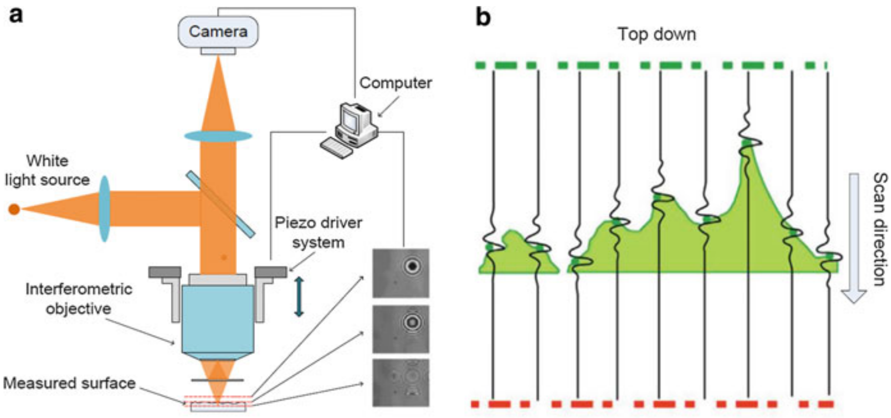


Fig. 8 (**a**) Schematic of vertical scanning interferometry; (**b**) localization of coherence peak using VSI technique (Tang 2016)

Ltd. (vertical resolution of 0.1 Å), NewView 7300 (vertical resolution smaller than 0.1 nm), and APM650 (areal measurement of high aspect ratio features) from the ZYGO Corporation. However, a large amount of interferograms are required to calculate the coherence profile, which significantly limits the measurement rate of VSI. The vertical mechanical scanning also requires extra calibration and compensation process before the in situ/offline measurement.

Wavelength Scanning Interferometry

Wavelength scanning interferometry (WSI) is proposed for the first time by Takeda and Yamamoto (1994). It takes advantage of shifting the phase by tuning wavelengths of broadband light source without any mechanical scanning. As the wavelength varies, the phase difference between the measurement arm and reference arm changes, resulting in sinusoidal intensity variations of individual pixels. Absolute surface position of each point can then be determined through frequency analysis of the intensity variations. To analyze the fringes and retrieve the phase information, various algorithms have been developed based on the zero-crossing technique, fast Fourier transform (FFT), and convolution and Carré algorithm. WSI can characterize both the rough and smooth surfaces without 2π phase ambiguity. It can also be extended to measure film thickness measurement through separation of interference signals from the top and the bottom of film surface in frequency domain (Gao et al. 2012; Ghim and Kim 2009).

Compared with CCI/VSI, the wavelength change rate is over mechanical scan rate. The camera exposure time and the computing time for data processing are factors limiting measurement rate of WSI. It is highly computationally intensive for areal measurement as a large number of frames need to be captured and analyzed for each areal measurement. The wavelength change is also very sensitive to the environmental noises such as mechanical vibration and air turbulence. To minimize the environmental effects and achieve the high measurement accuracy, Jiang et al.

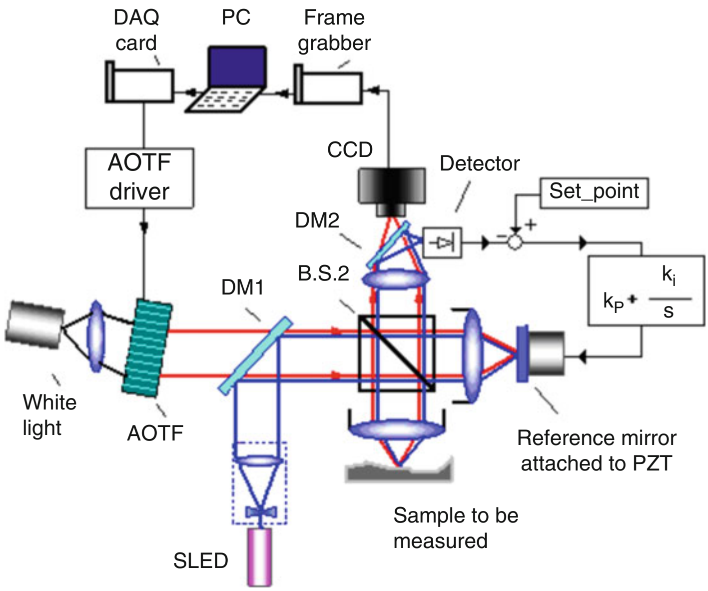


Fig. 9 An enhanced WSI with an active servo system to eliminate the environmental noise (Muhamedsalih et al. 2013)

proposed an enhanced WSI which introduced an active servo control system (reference interferometer) to monitor environment noise and compensate the environment-induced measurement error, as shown in Fig. 9. This reference interferometer is utilized as a feedback source for a close loop control system to stabilize the entire interferometry (Muhamedsalih et al. 2013). Most recently, this improved WSI has been successfully used in R2R process for surface defect inspection (Muhamedsalih et al. 2015).

Dispersive Interferometry

Dispersive interferometry, normally named spectrally resolved white-light interferometry (SRWLI) or white-light channeled spectrum interferometry (WLCSI), achieves phase shifting through wavelength variations without mechanical scanning. The interference beam is spatially dispersed by a diffraction grating or prism before being focused onto the camera, through which a channeled spectrum is obtained, and the phase information is encoded as a function of wavenumber along the chromaticity axis of the camera. Therefore, the surface profile can be obtained in a single shot, which largely improves the measurement rate of the interferometry with respect to the VSI and the WSI. Scanning the surface in XY plane is usually required for a dispersive interferometer to reconstruct surface topography.

In order to integrate the dispersed interferometry into production line, several variations of dispersive interferometry have been proposed recently, such as the spatially dispersed short-coherence interferometry (SDSCI), the line-scan dispersive interferometry (LSDI), and the dispersed reference interferometry (DRI). In particular, the DRI adds a dispersive element in the reference arm of the interferometer to separate the source light angularly by the wavelength. Because of the short-coherence nature of the light source used in DRI, the length of the measurement arm is determined by the most strongly interfering wavelength of light. Surface topography measurements are based on phase shifts due to wavelength variations, avoiding the problems caused by optical path difference scanning and phase-shift calibration (Fig. 10). The DRI has high axial resolution (nanometer level) and robustness to discontinuous and structured surfaces. In order to enable DRI the ability to perform on-machine surface topography measurement, a small, light, and compact fiber-linked probe was applied to separate the bulky and comparatively fragile interrogation optics from the measurement probe. High-resolution position data (2 nm resolution in axial direction) has been achieved by applying a template matching technique (Williamson et al. 2016).

Phase-Measuring Deflectometry

Phase-measuring deflectometry (PMD), also known as structured light and fringe projection, detects the distortions of a sinusoidal fringe projection upon a surface to determine the surface topography. The working principle of PMD is illustrated in Fig. 11. A digital laser projector (DLP) generates sinusoidal fringes on a rear projection screen (normally use computer software), and the fringes are projected onto the surface under test. From different viewpoints, the reflected fringe patterns from the specular surfaces appear deformed with regard to the slope variation of the measured surfaces. The distortions of fringes are then observed by one or more areal detectors, for example, a charged couple device (CCD) camera. After the proper calibration, the surface height information can be reconstructed through numerical integration of gradient data derived from the deformed fringes. Because two orthogonal local slopes data are needed to be integrated to reconstruct a 3D surface tomography, vertical and horizontal fringe patterns are usually needed to be displayed sequentially on an LCD screen. To further improve the measurement speed, cross-fringe pattern and color-fringe pattern (Fig. 12) were proposed to code multiple fringe patterns in one image (Zhang et al. 2017).

A significant strength of deflectometry is the adaptability to measure both specular and diffuse surfaces. Owning to its advantages of large dynamic range, non-contact operation, and high measurement rate, the PMD technique has been applied in several areas such as the measurement of freeform car body sheets (Sárosi et al. 2010), large aspherical and/or spherical mirrors (Su et al. 2012), and flaw detection of specular or semi-specular reflective surfaces (Chan 2008). Though robust to movements and environmental effects, the vertical resolution of current PMD system is still limited to microscale, and thus it is unsuitable for surface topography measurement. The measurement error resulted from the parasitic reflections from the rear surface of transparent screen optics should be

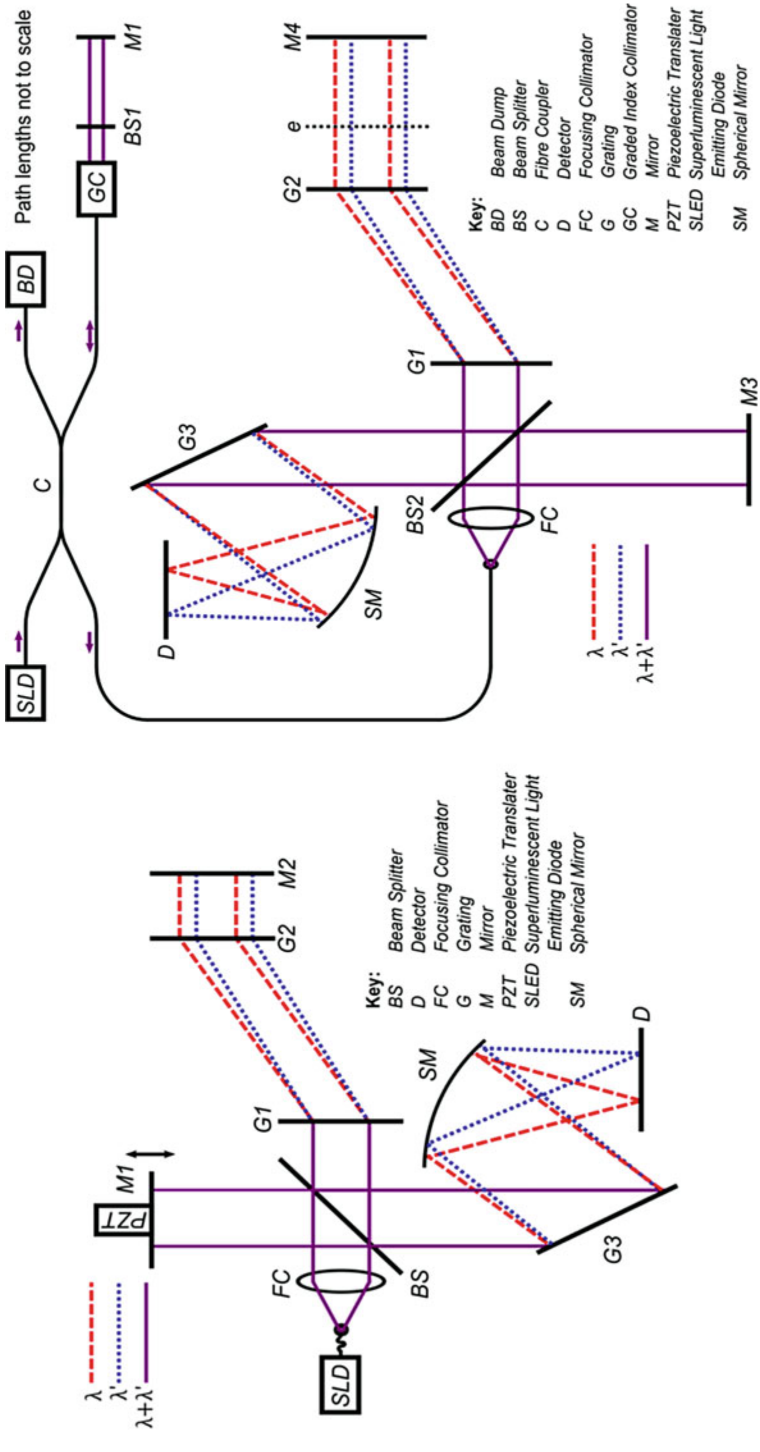


Fig. 10 Schematic of the experimental bulk optics dispersed reference interferometer (left) and DRI interrogation interferometer with a fiber-linked probe (right) (Williamson 2016)

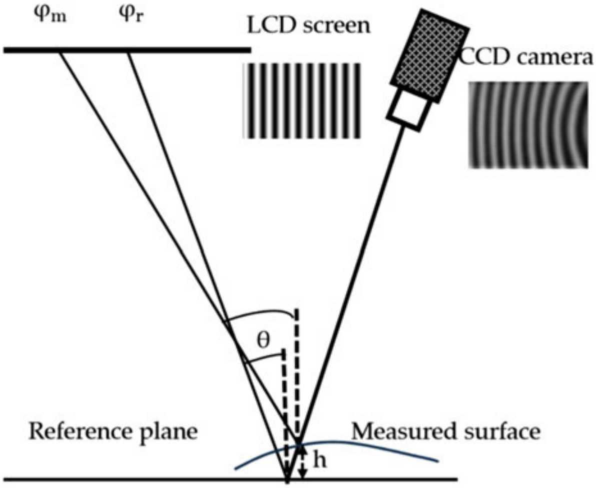


Fig. 11 Working principle of classical PMD to measure specular objects (Zhang et al. 2017)

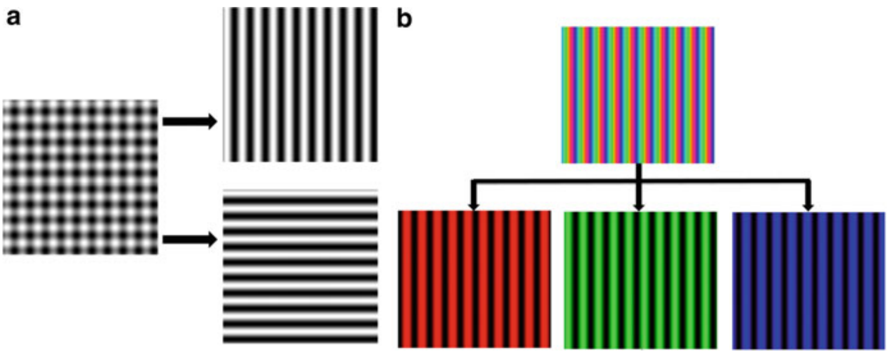


Fig. 12 (**a**) One crossed fringe pattern containing two orthogonal fringe patterns and (**b**) color composite fringe pattern containing three fringe patterns (Zhang et al. 2017)

carefully considered in order to further improve PMD measurement accuracy (Faber et al. 2012).

Focus Variation

Focus variation tracks the changing of image sharpness across the depth of field when mechanically moving an objective lens or the measured sample. The 3D topographical surface data is obtained through pixel-by-pixel calculation of image focus. As schematically shown in Fig. 13, the collimated beam is first brought to an objective and is focused onto the sample surface. All reflected rays then go back to the objective and are gathered by a camera through an imaging lens. Unlike other optical techniques where coaxial illumination usually is the only choice, various

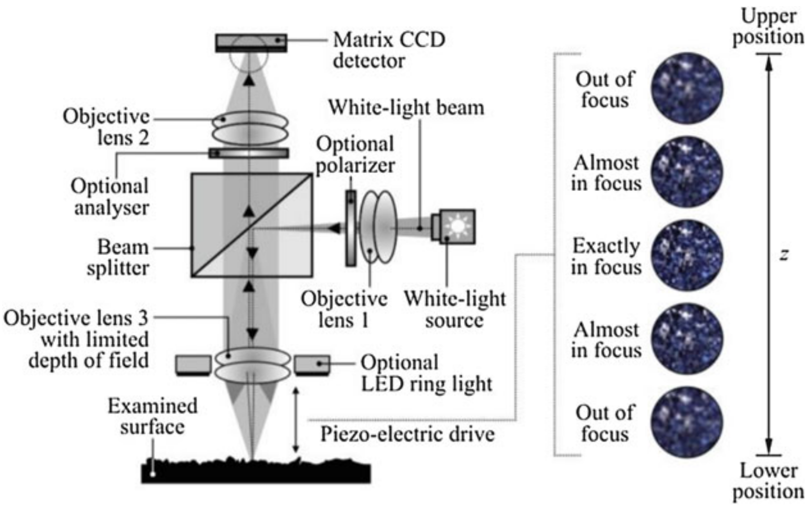


Fig. 13 Schematic diagram of measurement device based on focus variation (Wojciech Kapłonek et al. 2016)

illumination schemes can be used in focus variation instrument, for example, a ring light illumination can greatly enhance the measurable slopes of the system up to 80° (Danzl et al. 2011). The axial measurable range is dependent on the scanning range and the working distance of the objective. Additionally, the polarizer and analyzer showed in Fig. 13 can be used as filters to polarize the light when measuring metallic surfaces with steep and flat surface elements. Commercially this has resulted in the infinite focus range of offline measurement instruments by Alicona Imaging GmbH (Fig. 13).

The absolute nature of the focus variation method allows measurement of discontinuous surfaces containing steep, broken or rough regions, and the spatially separated regions. This method has excellent measurement range (up to 25 mm) with 10 nm achievable axial resolution, making it applicable to surfaces with complex structures and large discontinuities. Compared with interferometric-based methods, it is less susceptible to short-term variations in ambient light, temperature, humidity, and pressure.

However, the requirement for mechanical scanning in height direction makes the focus variation somehow a slow method. The measurement rate is less than 1 Hz, making it sensitive to vibration and inappropriate for in-line/on-machine measurement. Another negative aspect is the necessity for nanoscale surface roughness to back scatter sufficient light for sharpness detection.

Despite these limitations Alicona offer the IF-SensorR25, IF-Portable, and IF-Robot for metrology in production environments. IF-SensorR25, a miniaturized version (126 × 153 × 202 mm) for integration with machine tools, has been reported as beneficial for measurement in electro-discharge machining (EDM) centers, allowing a fourfold increase in machining accuracy (Williamson 2016).

IF-Portable and IF-Robot are offered as roughness, waviness, and form measurement tools for use in production environments with a focus on the ability to measure on and around traditionally difficult to measure larger components and assemblies. Focus variation instrument from Alicona was also applied as one of the characterization methods to investigate the additive manufacturing process such as selective laser melting and electron beam melting (Triantaphyllou et al. 2015).

Embedded Metrology in Ultra-Precision Manufacturing

Contact Profilometer Based On-Machine Measurement System

Several contact profilometers have been employed for embedded on-machine surface measurement (OMSM) because of its technological maturity and the ease of integration. To ensure the similar or higher performance of measurement system used in OMSM, several modifications and specific setups are usually required. In this section, the applications of embedded on-machine measuring system (OMMS) in ultra-precision manufacturing based on contact profilometer are introduced with emphasis on the principle and accuracy achieved.

Suzuki et al. (Suzuki et al. 2008) applied a new contact type of on-machine measuring system to measure aspherical optical parts with a steep surface angle. In this measuring system, a ceramic air slider was adopted for the measurement probe, and a high-accuracy glass scale was employed to reduce the thermal drift of the displacement gauge. To reduce the change in the probe friction force, the air slider or the measuring probe was tilted to 45° against the aspherical workpiece axis. This configuration will keep the contact angle between the probe axis and the contact surface constant (Fig. 14b) when the probe was scanned over the workpiece surface.

Chen et al. employed a compensation approach to grind the tungsten carbide aspheric molds. In this approach, a contact probe based on-machine measurement was employed to eliminate the profile error (Fig. 15). A sapphire microprobe of 0.5 mm in radius was used to measure the ground profile on-machine. A new method was proposed to reconstruct the actual ground profile based on the measured profile data. The overall profile error after grinding was obtained by subtracting the target profile from the actual ground profile along normal direction and was then used to generate a new tool path for compensation grinding. The experimental results showed that after three compensation grinding cycles, the aspheric surface had a profile accuracy of 177 nm (in PV) with a roughness of 1.7 nm (in Ra) (Chen et al. 2010).

Contact probing systems are nowadays 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. It has been reported that this on-machine measurement function can improve the diamond machining accuracy for freeform optical surfaces. The on-machine contact measurement was utilized to align the remounting workpiece into the modified machining coordinate, while surface

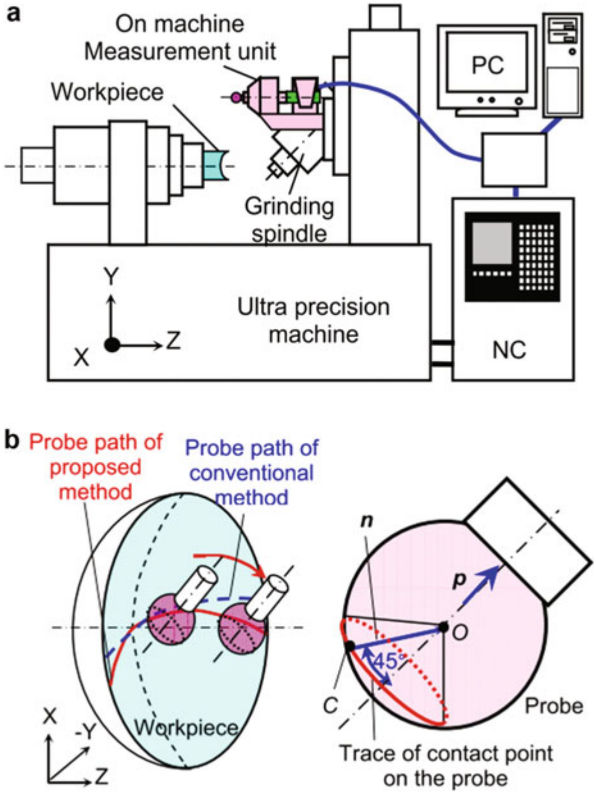


Fig. 14 (**a**) Schematic of on-machine contact probing for optics grinding process; (**b**) tilted angle probe configuration (Suzuki et al. 2008)

error derived from offline measurement was used for compensation machining (Zhang et al. 2015).

Nevertheless, the ruby ball used in the conventional contact probing system often has probe radius of several millimeters, which inherently limits lateral resolution of the measurement. Several attempts have been conducted to use scanning probe microscopes (SPMs) with tiny tips to realize on-machine measurement of ultra-precision machined micro-/nanostructured surface. As shown in Fig. 16, Gao et al. have designed an AFM head to measure diamond turned sinusoidal microstructures. A robust linear encoder was adopted in the AFM head for the measurement of profile height in the presence of electromagnetic noise. The OMMS was able to measure microstructured surfaces with 0.5 nm resolution in a spiral path (Gao et al. 2007).

Zhu et al. developed a scanning tunneling microscope (STM) probing system and applied the system in the ultra-precision fly-cutting process (Fig. 17) (Zhu et al. 2016). The probe tip follows the surface variations of the machined microstructure at a constant distance through the control of the difference between detected tunneling current and the default value. A piezoelectric translator (PZT) was used to drive the probe during the measuring process. A capacitance sensor was used to record the displacement of the driven piezoelectric translator (PZT) which reflects the profile

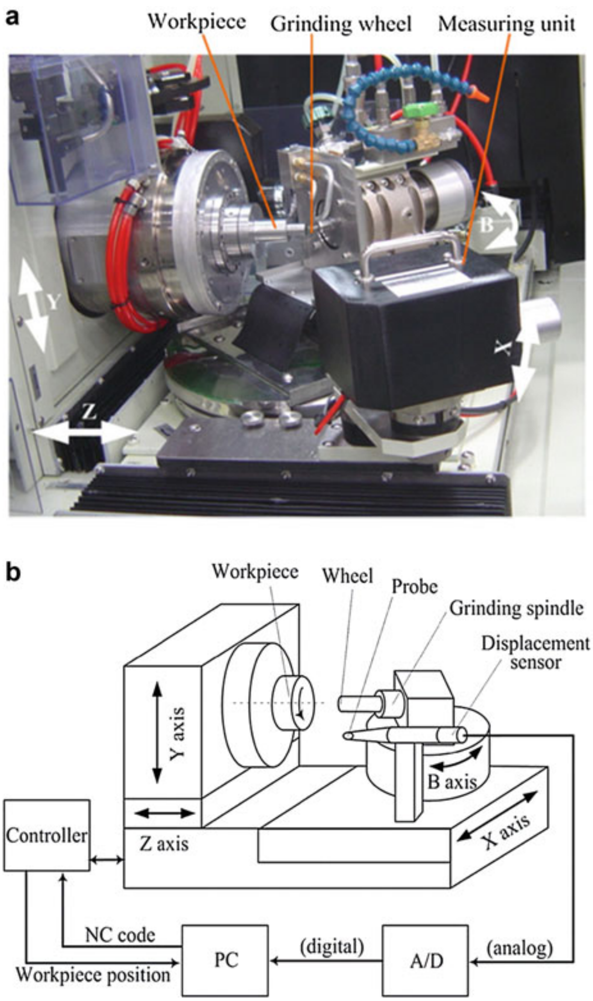


Fig. 15 (**a**) Mold grinding machine with integrated probing unit; (**b**) schematic of compensation grinding strategy (Chen et al. 2010)

measured surface. The geometrical size of the probe plays a key role on the measurement accuracy. Chemical etching process is well suited for the fabrication of tungsten probe with a stabilized stylus contour and ultra-sharp apex radius in high production reproducibility. Currently, tungsten probes with a controllable aspect ratio from 20:1 to 450:1, apex radius less than 20 nm and cone angle smaller than 3° can be achieved by the etching process (Ju et al. 2011).

Zhu et al. has employed this STM-based probing system to assist the precision fabrication of rectangular pyramid arrays. The STM-based probing system was mounted on the main spindle of an ultra-precision turning machine. The form accuracy of high-slope microstructures was significantly improved by cutting depth compensation of fly cutting in 120° direction through feedback of on-machine measured results (Zhu et al. 2016). The same probing system was also employed to

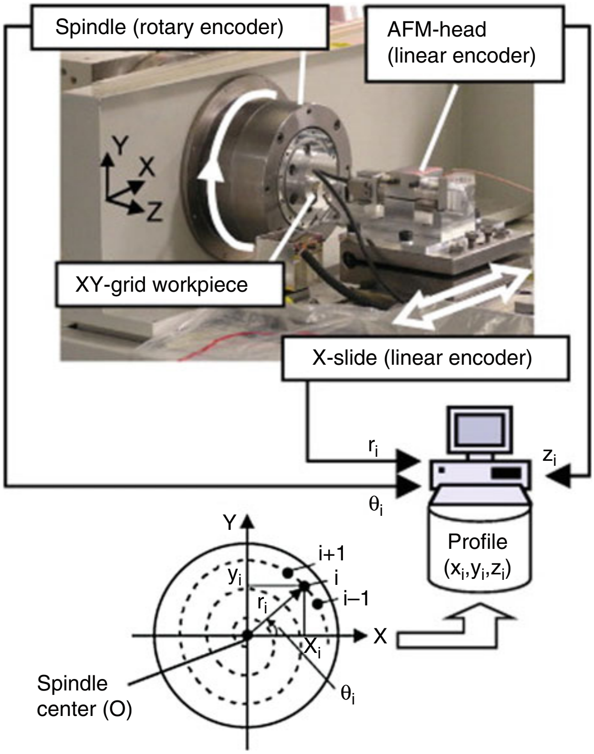


Fig. 16 Robust AFM based on-machine measuring system (Gao et al. 2007)

measure 3D curved compound eye surfaces machined by STS technique (Zhu et al. 2015). A tip-tracking strategy was proposed to extend the measuring ranges with more flexibility. Distortion caused by central alignment errors was analyzed based on the characteristic points.

Moreover, a piezoelectric force sensor was innovatively integrated into a FTS device to constitute a force-displacement servo unit termed as FS-FTS (Chen et al. 2015). The FS-FTS acted as a cutting tool with force sensor during the machining, and it was employed as a contact probe after the machining. The 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. proposed an in-process identification and repairment of diamond turned micro-lens arrays on a roll mold (Figs. 18 and 19). The thrust force was monitored during the machining process as an indicator to reflect cutting status and singular forces map with respect to the cutting tool position. After the defects were identified by FS-FTS scanning, the repair process was subsequently carried out (Fig. 19).

Additionally, a concept of relay fabrication was proposed based on the capability of FS-FTS on repositioning a new tool to the former cutting spot after the replacement of the worn tool (Chen et al. 2014). A bidirectional scanning strategy was

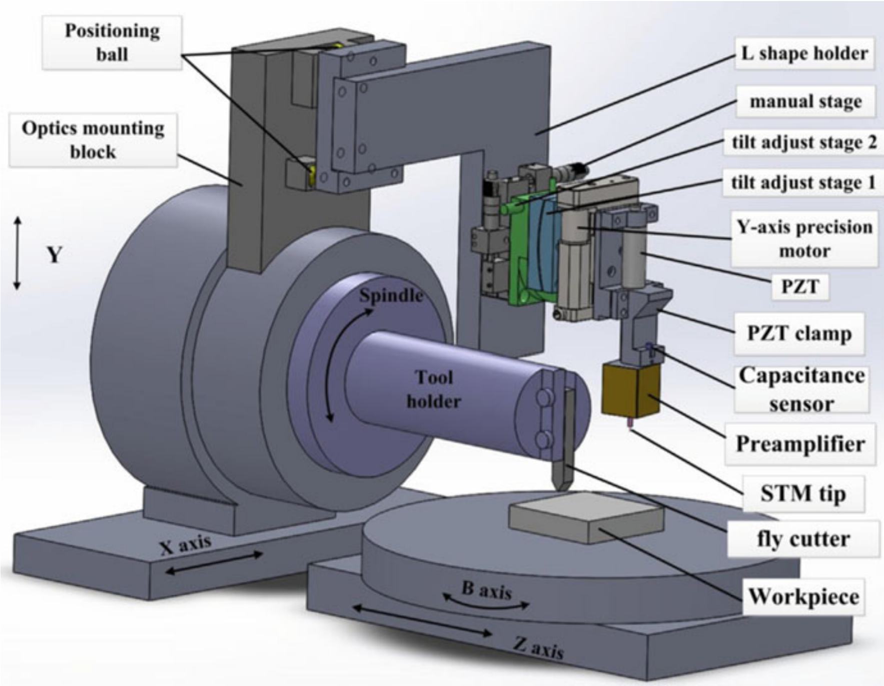


Fig. 17 STM-based on-machine measuring system with ultra-sharp tips (Zhu et al. 2016)

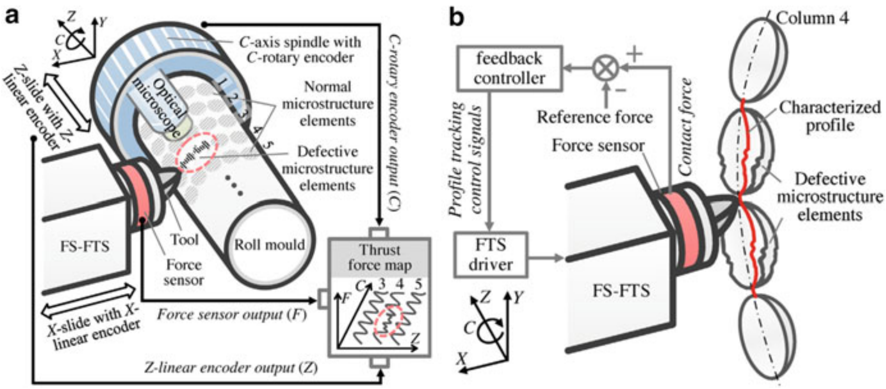


Fig. 18 Steps of the in-process measurement method for repair of destructive microstructures on a roll mold. (**a**) Step 1 for real-time detection of the micro-defect positions. (**b**) Step 2 for characterization of the micro-defect surface profiles (Chen et al. 2015)

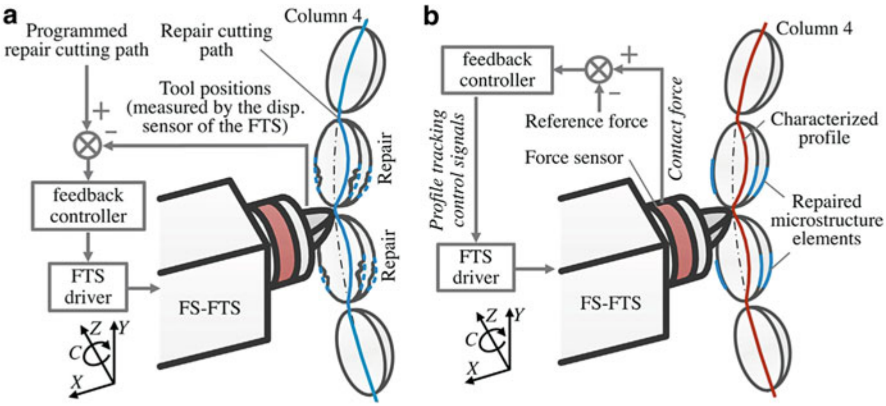


Fig. 19 The repair and evaluation steps. (**a**) Step 3 for repairing the defective microstructure elements. (**b**) Step 4 for evaluating the repair results (Chen et al. 2015)

employed to increase the positioning accuracy due to the delay of the feedback control loop. Stitching fabrication of a microgroove line array and filling fabrication of a micro-lens lattice pattern demonstrated the feasibility of the tool position measurement method.

Table 1 summarizes state-of-the-art researches on the contact profilometer-based OMMS and corresponding applications in ultra-precision machining processes.

Non-contact Optical On-Machine Measurement System

Non-contact optical measurement techniques are nondestructive and usually have high measurement rate, which makes them suitable for on-machine and in-process applications. Particularly for ultra-precision machining processes, on-machine interferometry has received a lot of attention from researchers for its nanometric precision and high-speed acquisition.

Shore et al. employed a Twyman-Green phase-shifting interferometer to conduct on-machine measurement of form accuracy of machined individual multi-mirror arrays used in the James Webb Space Telescope. The interferometer is mounted on a 3-axis machine with submicron positioning ability as shown in Fig. 20a. The measurement of form and radius was carried out using the cat's eye position (Fig. 20b), where the interferometer was focused on the surface and gave a quick measurement of mirror radius by measuring the displacement required to move from cat's eye to confocal positions. Achievable form accuracy of the individual mirror is reported below 20 nm RMS (Shore et al. 2006).

King et al. proposed an integrated solution for polishing and on-machine measurement of large-scale optics up to 1 m in diameter (King 2010). As shown in Fig. 21, it consisted of a Zeeko IRP 1000 polishing machine and a 5-axis motorized stage housing 4D dynamic interferometer. The dynamic interferometry

Table 1 Contact profilometer-based OMMS and applications

No	Author	Principle	Instrument	Performance	Applications	Remarks
1	Suzuki et al. (2008)	Contact ball	A high-accuracy glass scale with a ceramic air slider	Contact force <0.3 mN; 0.14 nm scale resolution	Steep optical mold grinding	The tilted angle configuration reduced the variation in the probe friction force
2	Chen et al. (2010)	Contact ball	N.A.	Similar to offline profilometer in terms of form deviation	Aspheric mold grinding	Normal-compensation tool path was generated according to the reconstructed profile from OMSM
3	Zhang et al. (2015)	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. (2007)	SPM	AFM head with a robust linear encoder	0.5 nm resolution	Microstructured 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. (2015)	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 microstructured surfaces (V-grooves and compound eyes)
6	Chen et al. (2015)	Piezo-force sensing	FS-FTS	Sub-mN contact force; 30 nm resolution	Microstructured surface machining	Defect repair and relay fabrication of micro-lens arrays were achieved with FS-FTS

is a variation of traditional PSI. Four phase-shifted interferograms are simultaneously generated through the use of a quarter wave plate and a pixelated birefringent mask in front of a single detector. The single-shot nature of the dynamic interferometry allows fast surface measurement without sensitivity to vibration or airflow through interferometer paths. The large optics were measured in situ without the need of risky transportation to offline metrology platforms, and corrective

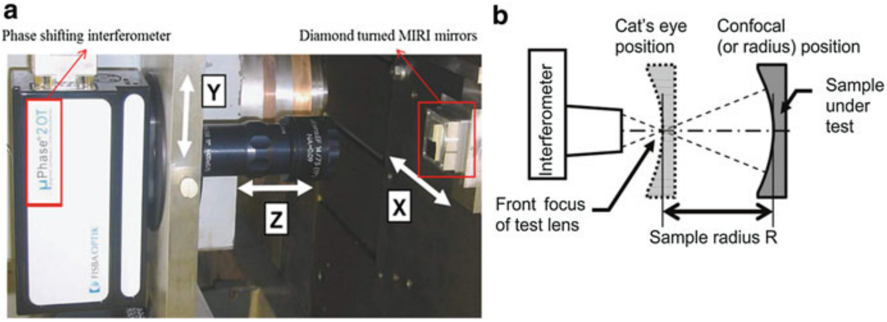


Fig. 20 PSI on-machine measurement of diamond turned mirror arrays (**a**) measurement system configuration; (**b**) measurement of form and radius (Shore et al. 2006)

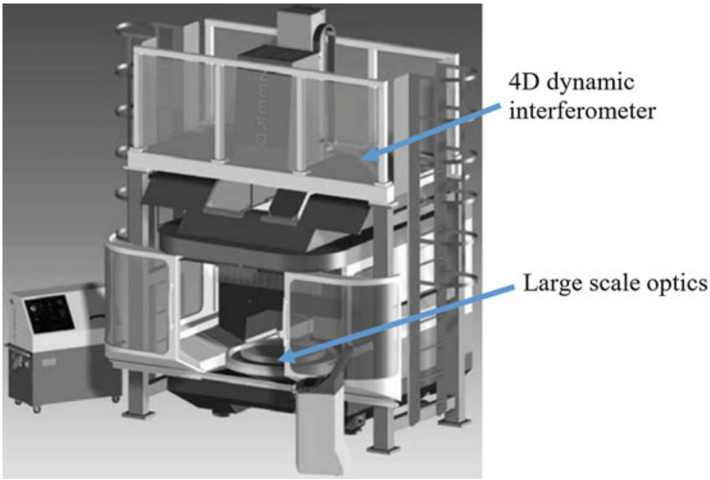


Fig. 21 Zeeko IRP 1000 machine, 5-axis motorized stage, and 6″ Fizeau interferometer (King 2010)

polishing was subsequently carried out. The measurement system was also equipped with different CGH elements to measure aspheric and freeform optics. Besides, a white-light interferometer for texture measurement and a laser tracker for radius measurement were integrated as optional accessories of the polishing machine.

In terms of microscale topography measurement, a wavelength scanning interferometer (WSI) based on wavelength division multiplexing was developed recently for the measurement of diamond machined-structured surfaces on a large drum turning machine. Jiang et al. created a new kind of full-field measurement to replace electromechanical scanning with white-light interferometry and to form a compact system that is fast, robust, and suitable for in situ surface measurement (Fig. 22) (Jiang 2011). An experimental system was developed for the manufacture of

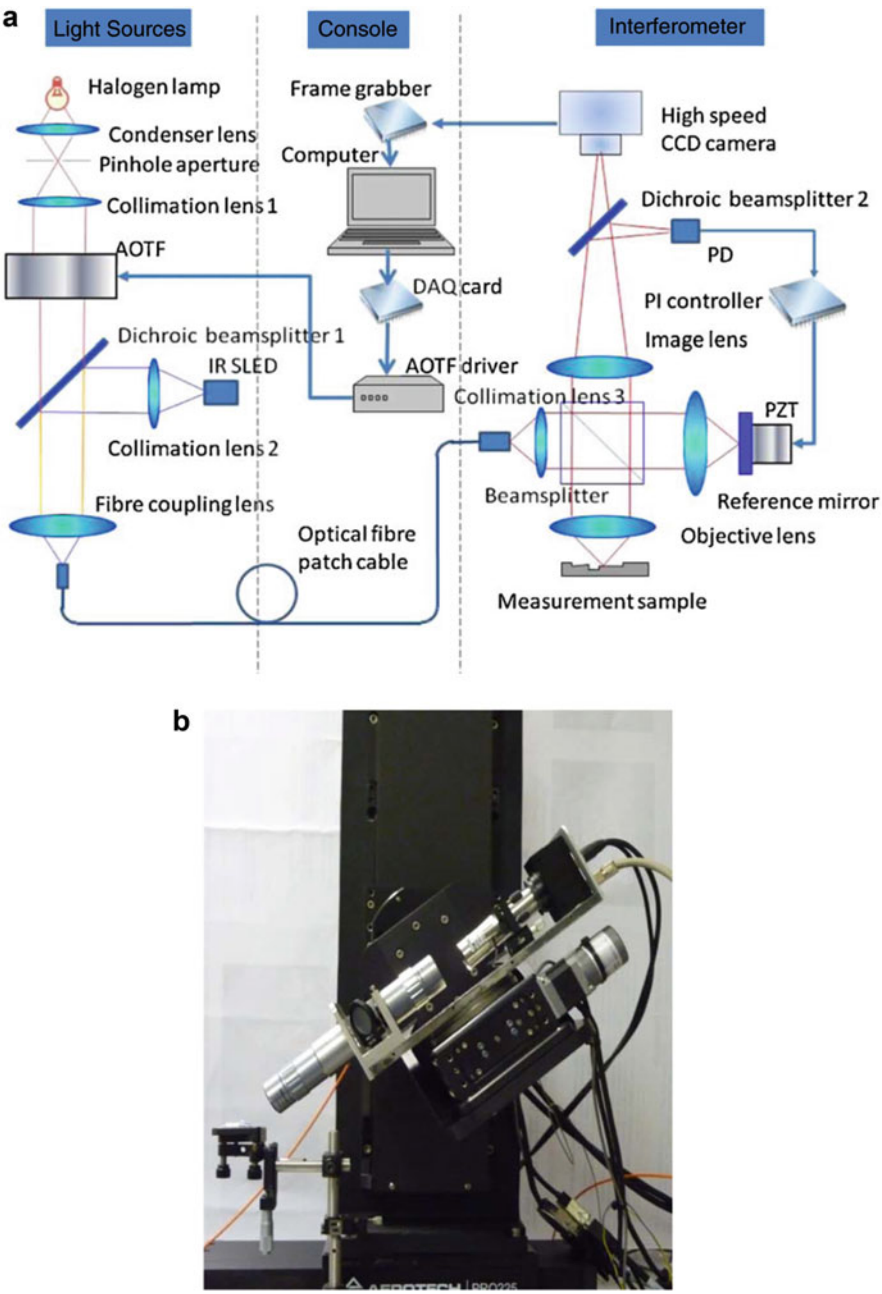


Fig. 22 The wavelength scanning interferometry system. (**a**) A schematic diagram; (**b**) a prototype system (Jiang 2011)

diamond turned/fly cut microstructured surfaces on a large drum diamond-turning machine. Nanometer precision surface measurement results were achieved for microscale structured samples. The instrumentation will have numerous further applications in precision machining, micro-machining, and the general manufacture of surface reliant products such as embossed steel sheet (Fig. 23) (Jiang 2011).

Due to the sensitivity to environmental disturbances and complex system configuration of interferometric instruments, non-interferometric OMMS have also been investigated in recent years. Röttinger et al. presented a setup of miniaturized deflectometry on a diamond-turning machine and measured high-precision specular surfaces without re-chucking operations (shown in Fig. 24). The development of global calibration and parasitic reflections reduction will boost the usage of deflectometry. The advantages of on-machine deflectometry include the

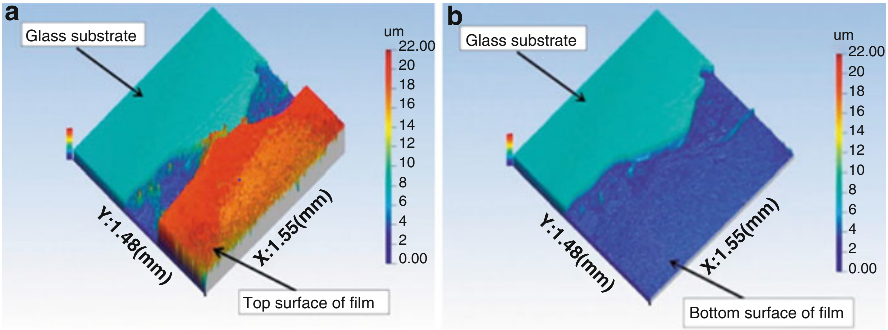
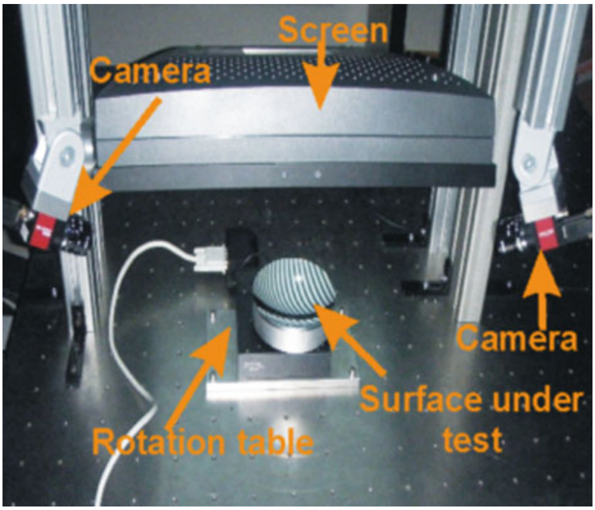


Fig. 23 Thin film measurement. (**a**) The top surface of the film forms a step upward on the glass substrate. (**b**) The bottom of the film surface forms a step downward on the glass substrate (Jiang 2011)

Fig. 24 Setup of PMD on a multi-axis ultra-precision machine tool (Röttinger et al. 2011)



environmental robustness and the capability of measuring arbitrary freeform surfaces within micron accuracy without additional 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 (Röttinger et al. 2011).

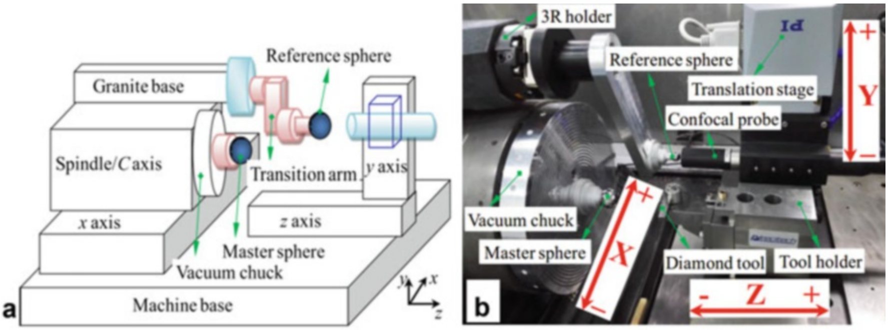
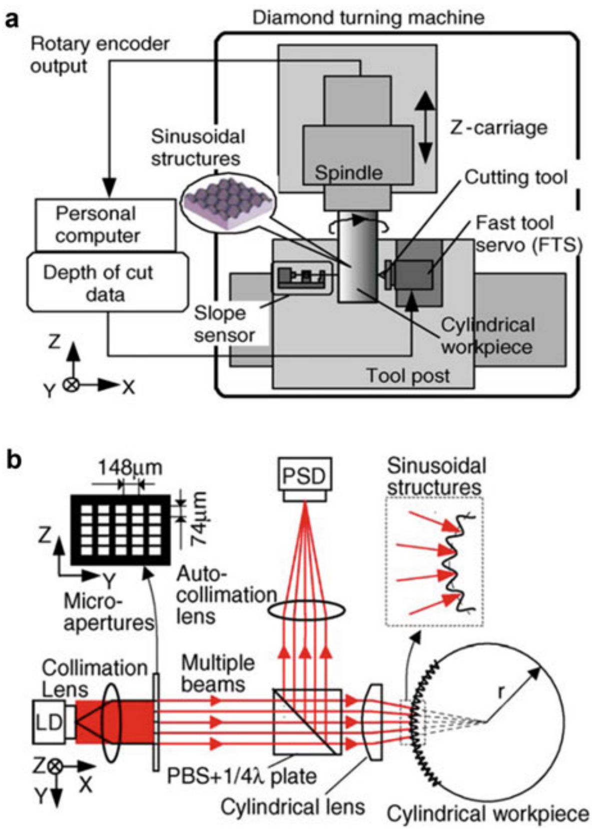


Fig. 25 Chromatic confocal based on-machine measurement for ultra-precision turning processes (**a**) schematic diagram of the OMM system; (**b**) image of the OMM system (Zou et al. 2017)

Fig. 26 Optical slope sensor for on-machine measurement of FTS machined sinusoidal structures. (**a**) Schematic of the fabrication and measurement system for the cylindrical master grid; (**b**) schematic of the slope sensor (Gao et al. 2006)



Confocal microscopy is an effective tool for surface measurement in the microscale. Compared with other optical methods, the maximum detectable slope can be as large as 75 degree with enough scattered light enhanced by software and hardware. All these characteristics make it applicable to measure complex and high-slope structured surfaces in the manufacturing environment. Zou et al. integrated a chromatic confocal sensor on a self-developed ultra-precision turning lathe for 3D measurement of diamond turned aspheric surfaces. As shown in Fig. 25, 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 (Zou et al. 2017).

Moreover, in order to characterize the functional-related geometric properties, several special OMMSs have been developed for corresponding applications. For instance, Gao et al. developed a two-dimensional optical slope sensor with a multi-spot light beam for on-machine measurement of local slopes of the FTS turned sinusoidal surface (Gao et al. 2006). As illustrated in Fig. 26, the sensor unit was mounted opposite to the cutting tool on the feeding slide. A cylindrical lens was integrated in the sensor so that slopes of the sinusoidal structures could be detected without the influence of curvature of the cylindrical workpiece. After machining, the surface was measured on the machine without removing the workpiece from the

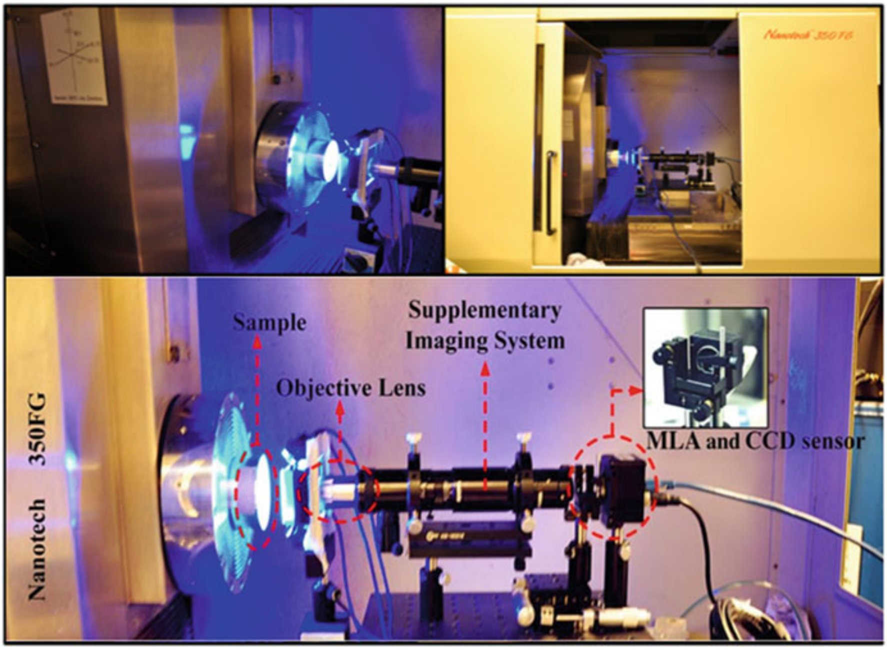


Fig. 27 Disparity pattern-based autostereoscopic system for in situ inspection of diamond turned microstructures (Li et al. 2015)

Table 2 Non-contact optical type of OMSM and applications

No	Author/ year	Principle	Instrument	Performance	Applications	Remarks
1	Shore et al. (2006)	Interferometry	Trioptics μphase PSI	1.9 nm repeatability	MIRI mirror diamond turning	Relative locations of confocal positions are evaluated with the aid of OMSM
2	King 2010	Interferometry	4D dynamics interferometry	30 μs acquisition time; 0.002λ wavelength precision	Large-scale optics polishing	Single shot and vibration insensitive measurement
3	Jiang (2011)	Interferometry	Wavelength scanning interferometer	15 nm vertical resolution; anti-vibration <300 Hz	Microstructures diamond turning on drum rolls	Real-time vibration compensation with a monitoring interferometer
4	Röttinger et al. (2011)	Deflectometry	Mini-PMD	Sub-micron accuracy	Freeform ultra-precision machining	Environmentally insensitive and able to measure arbitrary freeform without null testing
5	Zou et al. (2017)	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
6	Gao et al. (2006)	Autocollimation	Optical slope sensor with a cylinder lens	N.A.	FTS machining of cylindrical sinusoidal structures	The surface slope errors caused by the tool nose geometry were corrected with the integrated slope sensor
7	Li et al. (2015)	Auto-stereoscopy	Disparity pattern-based autostereoscopic 3D system	Sub-micrometer measuring repeatability	Pyramid structured surfaces machining	Compact, fast capturing, and environmental robust

spindle. Post-process compensation was carried out to further improve the machined surface quality. The results indicated that the error component caused by the round nose geometry of the tool was reduced from 0.632 mrad (10.1 nm in height amplitude) to 0.112 mrad (1.8 nm in height amplitude) through the post-process compensation, indicating the effectiveness of the proposed on-machine measurement system.

To overcome the rigorous environmental requirements for on-machine optical measurement system, Li et al. proposed a pattern-based autostereoscopic (DPA) 3D metrology system to capture raw 3D information of the measured surface in a single snapshot by a CCD camera (as shown in Fig. 27). A micro-lens array was used to capture raw 3D information, and the 3D digital model of the target surface was used to directly extract disparity information (Li et al. 2015). The direct extraction of disparity information (DEDI) method is highly efficient when performing the direct 3D mapping of the target surface because the tomography-like operation excluded the defocused information of every depth plane. Precise measurement results have shown that the proposed DPA 3D metrology system is capable of measuring 3D microstructured surfaces with sub-micrometer measuring repeatability for high precision and in situ measurement of microstructured surfaces.

The state-of-the-art research work on the non-contact optical OMMS and corresponding applications in ultra-precision machining processes are summarized in Table 2 with highlights on the performance and application remarks.

Conclusion

The ability to effectively monitor the machining process and measure products rapidly in manufacturing environment has become a fundamental limiting factor in the deterministic manufacturing of micro-/nanostructured surfaces with specific functions. Most of the measuring (dimensional and surface topography) systems used in micro-/nanoscale manufacturing is relatively slow, expensive, and in an offline manner.

This chapter has briefly introduced the typical embedded measurement systems used in manufacturing process. They have different performances with respect to range, resolution, measurement rate, and ability to measure discontinuous surfaces.

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 soft and delicate surfaces. Some SPMs are developed for some ultra-precision machining applications. However, the tip wear issue is still a big challenge for large area and long-time measurement. Non-contact methods which have fast measurement rate, high data density, and in nature preventing damage to delicate measurands or to the measurement instrument itself have been widely explored in this case such as machine vision, phase-shifting interferometry (PSI), white-light interferometry (WLI), wavelength scanning interferometry (WSI), dispersive interferometry, etc. With the development of calibration and processing algorithms, non-interferometric methods such as deflectometry and confocal chromatic microscopy (CCM) are receiving more attention in specific measurement conditions. However, for ultra-precision machining applications, robust interferometry is still the best choice because of its high measurement resolution (nanometer and even sub-nanometer).

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