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Review:

In-Process and On-Machine Measurement of Machining Accuracy for Process and Product Quality Management: A Review

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In-process and on-machine measurements are used to evaluate a variety of machining factors and conditions as well as the work done on the machine tool. With the increasing complexity of machining processes and greater requirements for accuracy and precision, the demand for advanced methods for process optimization has also increased. To meet this demand, process quality management (QM) requires an expansion of manufacturing metrology to include comprehensive closed-loop control of the machining process. To eliminate the effects of disturbances on the machining process and adjust the control quantities to optimal values for robustness, in-process and on-machine measurements are very essential. In this paper, we review technical trends in in-process and on-machine measurements for process QM and conventional quality control (QC) of products. Spreading measurement targets and applications are comprehensively reviewed.

Keywords: in-process measurement, on-machine measurement, manufacturing metrology, machine tools, quality management

1. Introduction

In-process and on-machine measurements were initially introduced as simple techniques for measuring workpieces on a machine tool, to compensate for machining error. As machining processes became more complex and greater precision was required, the need for improved methods for optimizing the processes increased. Progress in machine tools and measuring instruments requires the consideration of machine tool elements as well as setting and machining conditions.

As predicted by the "Taniguchi curves" in 1983 [1], the achievable accuracy for "normal machining" is 1 μm, that for "precision machining" is 0.01 μm, and that for "ultra-precision machining" is 1 nm. These were realized in 2000. Taniguchi highlighted the importance of in-process and on-machine measurements, noting, "machine tools/processing equipment and dimensional and surface quality measuring instruments have to be integrated into closed-loop control systems which will provide high accuracy acceleration velocity and position loop control between tools and workpieces, frequently at very high speed." Considering the requirement for reliable ultra-precision machine tools with accuracies on the order of 0.005 μm, various studies have been conducted on in-process and on-machine measurements, which were aimed at achieving a machining/process accuracy of 1 nm. In-process measurement, monitoring, and control techniques for machining processes were specifically introduced in 1989, and in-process techniques for tools, workpieces, and cutting processes and machine tools have been well reviewed [2–4]. Although part of the investigations focused on the automation of manufacturing processes, most were concerned with high machining accuracy and quality assurance of machined products.

Currently, commercialized in-process and on-machine measurement instruments implemented in machine tools have expanded the target accuracy from ultra-precision machining to precision machining. This was because of changes in the factors that affect machining accuracy and repeatability, such as unskilled operation of machine tools and control of process conditions, unregulated work material and tools in a globalized manufacturing environment, and harsh product requirements. Because the effects of these factors on the resultant machining accuracy are not independent but serial, in-process and on-machine measurement instruments were introduced for the purpose of checking the process [5]. Contacting probing systems have been particularly widely used for evaluating the settings and dimensional measurement of the workpiece and tool on a machine tool. ISO 230-10:2011 [6] was published as the first global standard for a machine tool probe, and specifies test procedures for evaluating the measurement performance of contacting probe systems (used in the discrete-point probing mode) integrated with numerically controlled machine tools. However, ultra-precision machining has progressed to a nanometer scale regime regarding positioning accuracy, which has accelerated its industrial application. In addition, the application of ultra-precision machining has recently spread to simultaneous multiple-axis control machining and combined machining to meet increasing demands for precision parts with complicated geometrical properties, such as three-dimensional complex forms, free forms, and fine surface figures [7]. To compensate for time-variable machining error when using a machining tool with a complex structure in real time, in-process and on-machine measurement techniques with accuracies on the order of 1 nm were tested.

In this paper, we review technical trends in in-process and on-machine measurements for process quality management (QM) and quality control (QC) of products. As a basic concept of in-process and on-machine measurements, the requirement for in-process and on-machine measurements based on the fundamentals of quality management and process capability are described in section 2. Section 3 is an overview of in-process and on-machine measurement techniques. In section 4, technical trends in each target and application are reviewed. In section 5, concluding remarks are made, together with comments on process and product quality management based on the concept of holistic measurement.

2. Basic Concept of In-Process & On-Machine Measurements

2.1. Quality Management and Process Capability

In the sense of the manufacturing metrology required for quality management (QM), the basic properties of in-process and on-machine measurements are common. In contrast to ordinary statistical quality control (QC) for assurance of machining accuracy by compensating for bias deviation or systematic error in the machining process, preventive QM is aimed at improving machining precision (repeatability) by decreasing accidental and random errors in the machining process; that is, it is aimed at improving the process capability.

Process capability is the ability of a process to produce outputs within the specification limits, and it is generally expressed by statistical measures defined as the process capability indices C_p and C_{pk}. Assuming the process output is approximately normally distributed, these indices are derived from statistical values, namely, the mean $\bar{x}$ and standard deviation s of an appropriate number of samples. These correspond to the estimated mean of the process and the estimated variability of the process, respectively. If the upper and lower specification limits of the process are denoted by USL and LSL, respectively, the tolerance range T is given by the widths of USL and LSL. If the process mean is centered between the specification limits, the process capability index C_p will express the spread with respect to the tolerance range, which is given by

$$C_p = \frac{\text{ULS} - \text{LSL}}{6s} = \frac{T}{6s} \quad \ldots\ldots\ldots \quad (1)$$

If the process mean is not centered, C_p would overestimate the process capability. Hence, considering that the process mean may not be centered between the specification limits, the process capability index C_{pk} represents the process deviation with respect to the tolerance range, which is given by

$$C_{pk} = \min\left(\frac{\text{USL} - \bar{x}}{3s}; \frac{\bar{x} - \text{LSL}}{3s}\right) \quad \ldots\ldots \quad (2)$$

For sufficient reliability, interval estimation is carried out as a statistical procedure that reveals the accuracy of a point estimation for each of the standard deviation and process capability indices using the results of measurements. The confidence interval of the standard normal distribution can be estimated by an χ^2-distribution using the following equation:

$$s^2 \frac{n-1}{\chi^2_{n-1;1-\alpha/2}} \leq \sigma^2 \leq s^2 \frac{n-1}{\chi^2_{n-1;\alpha/2}} \quad \ldots\ldots \quad (3)$$

where $n-1$ (n is the sampling number) and $1-\alpha$ (α is the critical rate or level of significance) are the degrees of freedom and confidence level, respectively.

2.2. Measurement Uncertainty and Process Capability

The measured values are affected by the measuring instrument, the measured object, the operator, the environment, and the measurement strategy. The uncorrected systematic and random deviations that remain after calibration and surveillance are stated as the uncertainty of the measurement U at GUM [8]. A common description is that the uncertainty is the interval that contains 95% of the measured values.

According to Weckenmann et al. [9], a real machining process situation is falsified through the "eyes of the measuring instrument" because the uncertainty of the measurement by the measuring instrument overlaps the deviation of the production process. It is generally considered that a measuring instrument should have an uncertainty of measurement U of 10% – 20% of the tolerance range T based on the Golden Rule of Metrology: $U = 0.1\ T$ – $0.2\ T$. When measuring a real machining process, the effect of the measurement uncertainty on the observation of the real processes must be taken into consideration, as shown in **Fig. 1**. The standard deviation of the process, s_P, and the standard deviation of the measuring instrument, s_M, overlap, thus resulting in a total deviation s given by the following equation:

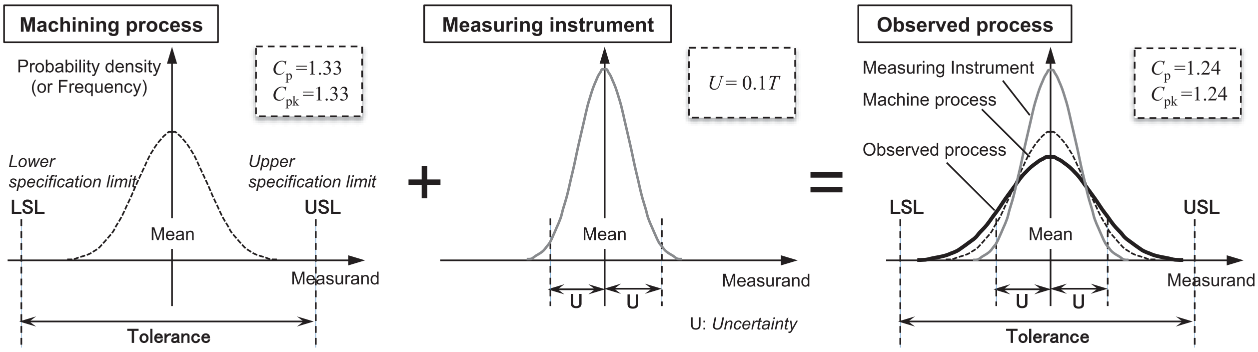
$$s = \sqrt{s_P^2 + s_M^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

where s_P and s_M are given by

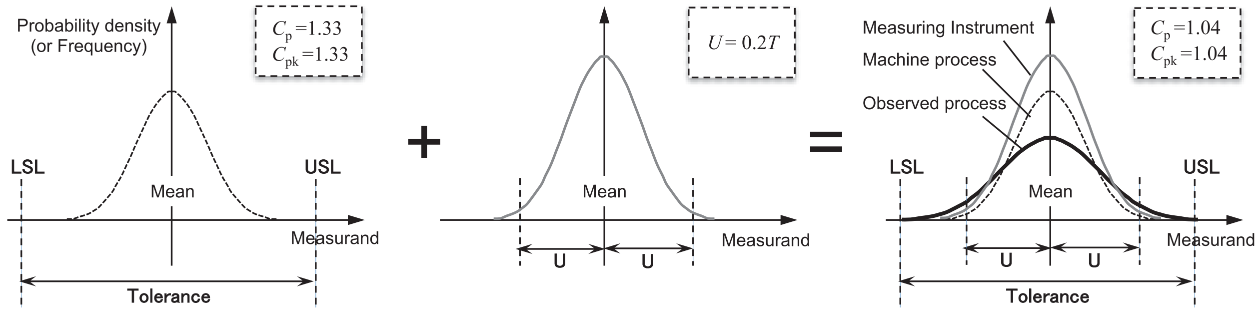
$$s_P = \frac{T}{6C_P} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$s_M = \frac{U}{1.96}; \quad for \quad (1-\alpha) = 95\% \quad \ldots\ldots \quad (6)$$

In actual situations, by using a measuring instrument with measurement uncertainty $U = 0.1\ T$, the real process capability $C_p = 1.33$ will be reduced to $C_p = 1.24$. A measuring instrument with $U = 0.2\ T$ will be made worse, resulting in a value of C_p close to 1.0. Thus, machining



(a) Observed process for a measurement uncertainty of $U = 0.1T$.



(b) Observed process for a measurement uncertainty of $U = 0.2T$.

Fig. 1. Effect of measurement uncertainty on observation of real processes [9].

processes are assessed as being worse than they really are. Therefore, adequate knowledge of the consequences and effects of the uncertainty of measurement are necessary to attempt the introduction of effective in-process and on-machine measuring instruments for assessing machining processes, setup, and control.

2.3. Expanded Role of Manufacturing Metrology

As indicated in **Fig. 2**, manufacturing metrologies are categorized as pre-process, in-process/on-machine, and post-process measurements. Although there is no clearly defined categorization terminology, the above have been differentiated by the time and place in which a measuring instrument is used, and sometimes by its role in the entire process. Conventional manufacturing metrology for QC is post-process measurements, which is performed after a process has been completed using measuring instruments set in a well-controlled place separated from the machining tools. The product is inspected using a gauge, a simple measuring instrument, and a coordinate measuring machine (CMM) to check a goodness of fit. In the case of QC based on post-process measurement of the product, the machining accuracy can be indirectly managed and assured. The post-process measuring instruments must be calibrated to ensure traceability. Pre-process measurement is usually used to prepare for a process. In-process and on-machine measurement are carried out during a process to evaluate a wide variety of factors and conditions of the machining process as well as the work done on the machine tool. The terms in-process measurement and in situ measurement are sometimes used without clear differentiation. In this paper, for example, in work measurement, the term in-process measurement refers to measurement of the work performed on the machine tool during the machining process. However, the term in situ measurement refers to a measurement that interrupts the process while the workpiece is held in the work holder.

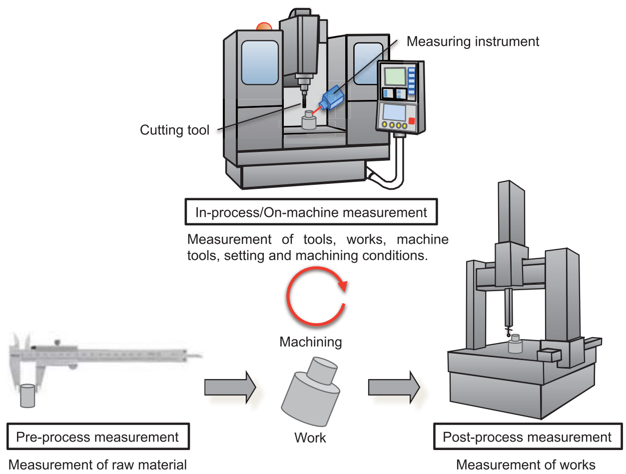


Fig. 2. Manufacturing metrology categorized by process: pre-process, in-process and on-machine, and post-process measurements.

As machining processes became more complex and greater accuracy and precision were required, the demand for advanced methods for process optimization increased. To meet this demand, process QM requires an expansion of the role of manufacturing metrology, as shown **Fig. 3**. The primary role of conventional manufacturing metrol-

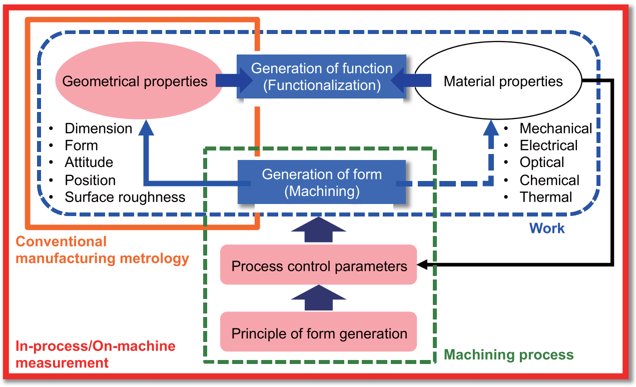


Fig. 3. Expansion of the role of manufacturing metrology to generating function of products.from conventional manufacturing metrology to comprehensive manufacturing metrology with in-process and on-machine measurements.

ogy is the assessment of the geometrical features of a machined work, such as the dimensions, form, attitude, position, surface roughness, and waviness. Therefore, the strategy of conventional manufacturing metrology focuses on the QC of the product. However, the geometrical features of a machined work are generated based on the machining principle of form generation. To eliminate the effects of disturbances in the machining process and adjust the control quantities to optimal values for robust processes, in-process and on-machine measurements are very essential. In-process and on-machine measurements serve the purpose of comprehensive closed-loop control of the machining process (both functionalization and forming) and the assessment of the geometrical features of the machined work. Because the machine tool, tool, workpiece, machining condition, machining process strategy, machining environment, and operator all affect the machining process capability, the strategy of comprehensive manufacturing metrology using in-process and on-machine measurements focuses on the QM of the product including the machining process.

2.4. Requirements for In-Process and On-Machine Measurements

The requirements for in-process and on-machine measurement techniques include the specific and basic properties mentioned in the discussion of the relationship between a measurement uncertainty and the machining process capability. Moreover, it is inadequate to examine the required properties for in-process and on-machine measurement techniques without taking into consideration the interactions with the machining process, arrangement, and operation. **Fig. 4** shows the specific properties required for the in-process and on-machine measuring instruments for machining process control. These properties are necessary to maintain robust core-performance measurement, which is affected by the measured object, a variety of factors of the machining process, and the process operations. A robust core-performance measurement of not only the static characteristics but also the dynamic characteristics requires repeatable quantitative measurement results for QM of the product including the machining process. The requirements for environmental, hardware, and software factors are specific to the in-process and on-machine measuring instruments. For example, when measuring a three-dimensional machined form in contact with the machining tool during the machining process using an optical interferometer, properties of the measuring instrument for example, environmental properties such as anti-vibration and mist-proof, hardware properties such as high measuring speed and compact design, and software properties such as high-speed signal processing and stitching data processing should be taken into consideration. Effective in-process and on-machine measurements enable the control of the measured quantity with regard to the measured object during the machining process.

3. Background and Overview of In-Process and On-Machine Measurements

The term on-machine measurement refers to the spatial position of a measurement target such as a workpiece, tool, machine tool, or machining environment. In contrast, the terms pre-process measurement, in-process measurement, and post-process measurement refer to time in the broad sense of a process or operation, including factors such as error compensation for a machining tool. Based on these definitions of the terms, a map of measurement techniques on the spatial and time axes is shown in **Fig. 5** to clearly illustrate the position and the role of the measurement techniques during a process. Moreover, the spreading measurement targets and applications of in-process and on-machine measurements are also illustrated in **Fig. 5**. For example, an in-process measurement of a cutting tool is plotted as Tool on the spatial axis and as In-process/On-machine measurement on the time axis.

Plot [*a*] in **Fig. 5**, "In-process measurement and workpiece-referred form accuracy control," was developed in 1980 as the pioneer of the fast tool servo to improve the stability and repeatability of ultra-precision diamond turning processes. This occurs in the following context, the rapid progress in ultra-precision machining tools has just begun. Kohno et al. [10, 11, 12] proposed the principle of the workpiece-referred form accuracy control method using the micro-tool servo with the in-process measuring instrument of the high-precision optical surface sensor (HIPOSS), the schematic of which is shown in **Fig. 6**. The principle of the HIPOSS is based on point autofocus with an accuracy of less than 1 nm. The method was improved to the nanomachining technique used to form a free-form surface with the aid of in-process measurement using an absolute reference [13]. It has been proved that machining error compensation by means of direct process control based on in-process measurement is sufficiently effective for increasing machining process capability.

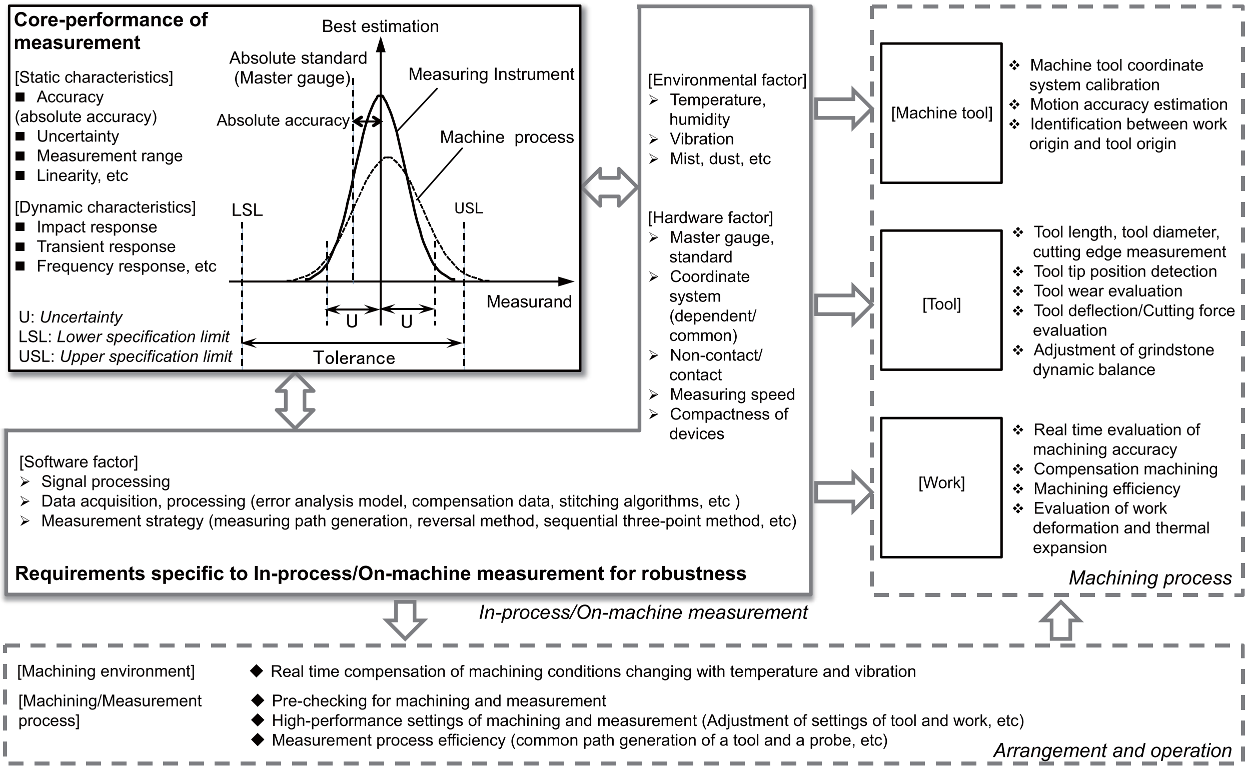


Fig. 4. Specific required properties of in-process and on-machine measuring instruments for machining process control.

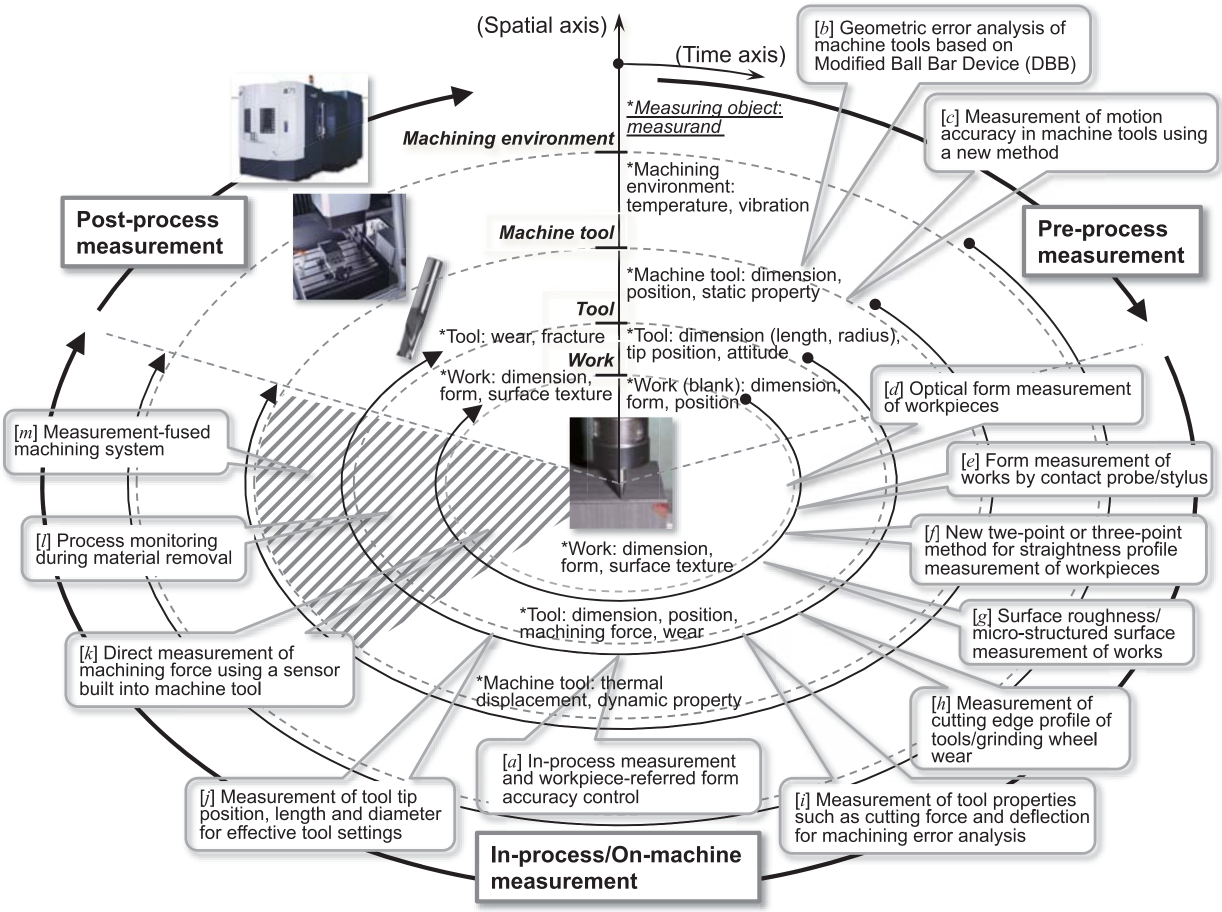


Fig. 5. Spreading measurement targets and applications of in-process and on-machine measurements.

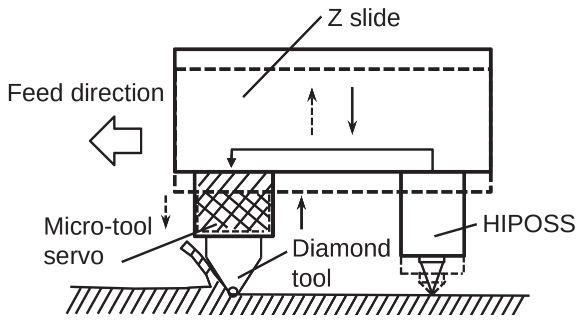


Fig. 6. Principle of workpiece-referred form accuracy control [10].

4. Technical Trends in In-Process and On-Machine Measurements

4.1. Geometric Error Analysis of Machine Tools

To analyze the geometric errors of a machine tool, pre-process measurements are performed on the machine. The analysis is essential for QC to assure machining accuracy by compensating for systematic errors in the machining process. On-machine measurement methodologies of geometric errors in machine tools are divided into direct and indirect measurement methods. Direct measurements are used to analyze single errors such as the linear positioning error and angular error of individual axes, whereas indirect measurements are used to analyze volumetric error. In particular, indirect measurement schemes for the kinematics of three orthogonal linear axes and five-axis kinematics with two rotary axes were well reviewed in [14].

A ball bar is widely used for measuring the motion accuracy of machine tools [15]. Plot [*b*] in **Fig. 5**, "Geometric error analysis of machine tools based on modified double ball bar device" shows recently developed on-machine measurement methods for assessing the accuracy of multiaxis machines such as five-axis machining centers. In the improved double ball measurement method, motion error sources on five-axis machine tools are identified using the modified double ball measuring device [16] and conic trajectories measured by a double ball bar [17].

In plot [*c*] in **Fig. 5**, "Measurement of motion accuracy in machine tools using new method," new approaches to verifying the performance of machine tools are proposed. The volumetric error of a machine tool using a laser tracker has been investigated [18]. The various sources of error that affect the measurement uncertainty of the laser tracker, additional sources of error that increase the uncertainty, and factors that affect these techniques were discussed in detail. The ball bar and the new measuring instrument that links the $X-Y$ and spindle axes are joined by a bearing developed for measuring the coordinates of the motion paths under simultaneous five-axis control for $X-Y$ axes, and in the spindle direction for three axes. Using this device, the feasibility of the motion accuracy measurement system was demonstrated, and it can be used to estimate various types of motions such as linier motion, circular motion, and continuous curved motion under simultaneous five-axis control [19]. In contrast, Trapet et al. [20] developed a new type of self-centering probe that was designed as three independently movable probe styli that form a miniature coordinate-measuring machine with parallel kinematics. The probe was placed in the spindle of the machine tool and a ball artifact on the work table. In the ultra-precision machining process region, measurement and compensation for error motions with an accuracy on the order of nanometers using the new on-machine measurement and calibration method have been attempted to compensate for systematic error [21].

4.2. Measurement of Geometrical Parameters of Workpieces

The direct assessment of the geometrical features of a workpiece during machining is essential not only for eliminating the effects of disturbances on the machining process but also for suppressing the uncertainty of the measurement. Both high process capability and accurate process capability estimation can be achieved by in-process and on-machine measurements of a workpiece. Particularly, in-process and on-machine measurements are very important for ultra-precision machining because it requires tolerance on the order of several tens of nanometers. The practical purpose is to make the repeated correction processes efficient and enable compensation for accidental and systematic machining errors by direct process control. To meet these demands, high-precision optical measurement methods were initially developed. The methods were modified for in-process and on-machine measurements, which are shown in plot [*d*] in **Fig 5**, "Optical form measurement of workpieces," Although the accuracy of interferometric methods are sufficiently high for them to be applied to ultra-precision machining processes, they are easily affected by disturbances such as vibration and air turbulence in the optical paths. Shape measurements by ultra-precision diamond turning of spherical or aspherical optical mirrors were performed using interferometric methods. Improved measuring instruments such as a Fizeau interferometer, zone-plate interferometer, and lateral-shearing interferometer were mounted on a modified lathe to examine the measurement performance while the machine was running. Owing to the vibration of the running machine tool, it was impossible to achieve robust measurements using a Fizeau interferometer [22]. To overcome this drawback, it was replaced by a zone-plate interferometer [23]. Because of the common path of the interferometer, it was slightly affected by air turbulence and machine vibration. The shape error of a spherical mirror produced using a cutting machine was successfully measu red while the machine was running. However, the complex configurations of a zone-plate interferometer make it too expensive to be widely used. A feasibility study of the practical application was conducted using a common path lateral-shearing interferometer with a minimum number of optical components [24]. **Fig. 7** is a schematic diagram of the developed lateral-sheering

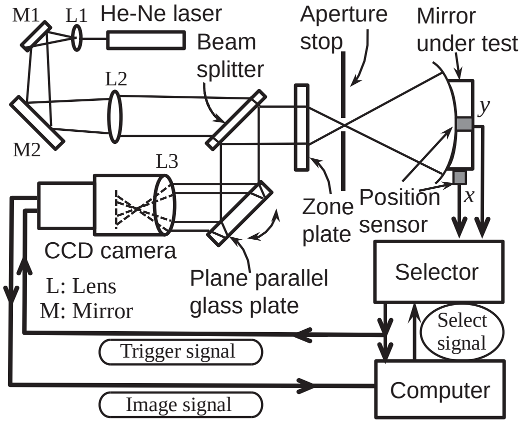
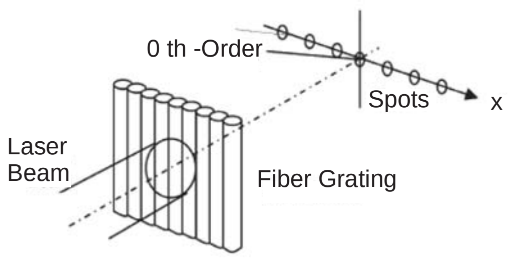
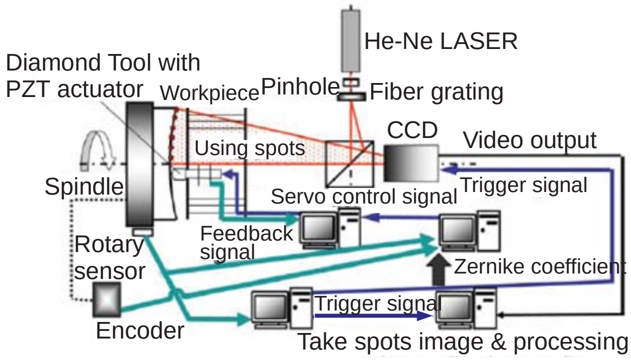


Fig. 7. Schematic diagram of lateral-sheering interferometer [24].



(a) Generation of multi-optical-beams by a full-line fiber grating.



(b) Experimental set up for figure turning control.

Fig. 8. Figure error control for diamond turning by in-process measurement based on half-line Hartmann test [26].

interferometer. The beam is diffracted at the zone plate to the mirror being tested. The zone plate functions as a null lens. A plane parallel glass plate is used to shear the wavefront of the recollimated light; that is, lateral-shearing interference fringes are produced by the difference between the optical path of the wave front reflected from the front surface of the parallel glass plate and that reflected from the rear surface. Two metallic concave mirrors, namely a spherical one and a parabolic one, were measured using the interferometer while the machine was running. The use of a radial-shearing interferometer with two zone plates in which the measuring wavefront from the entire mirror surface under test is referred to that from the central part was developed as a more advantageous method for on-machine measurement of an axi-symetric concave mirror compared to the use of a lateral-shearing interferometer [25]. The interferometer is sufficiently stable to be applicable to in-process measurement using diamond turning with an accuracy of about 0.06 μm $P-V$ while the machine is running at 1000 rpm.

Besides interferometric methods, the Hartmann test, chromatic confocal method, and optical triangulation method have been improved for in-process and on-machine measurements. The half-line Hartmann test is particularly used for in-process figure measurement of large mirrors [26]. **Fig. 8** shows the figure error control for diamond turning by in-process measurement based on the half-line Hartmann test. By means of "full-line" multioptical-beams generated by line fiber-grating, as shown in **Fig. 8(a)**, a radial section figure can be measured using the "half-line" multispot image reflected by the concave mirror under test. By detecting the spot image using a charge coupled device (CCD), the image is analyzed for the height distribution along the spots and the mirror figure error map. **Fig. 8(b)** shows the experimental setup for figure turning control based on the half-line Hartmann test. By cutting from the center to the edge, in-process measurement is executed periodically. A microtool servo is controlled by the deviation of the newest measured form from the ideal. Experimental results have clearly shown a reduction in the figure errors and confirmed the possibility of turning error correction by the method. A chromatic confocal distance sensor was installed on the wheel head of the cylindrical grinding machine (CGM) used for high-precision grinding of noncircular contours to meet new demands for process monitoring and in-process measurements [27]. Because chromatic aberration is used, each focal point, or the distance between the sensor and the work surface, corresponds to a particular wavelength. The most significant advantage of this measuring principle is its insensitivity to different surfaces with different reflectivities; it is also suitable for shiny surfaces. The functions of the orientation (C-angle) measurement of the workpiece in the CGM and its diameter and profile measurement are supplied to the measuring system. These in-process measurements enable reduction of set up time for the precision grinding of a noncircular workpiece, the optimization of the grinding process, and assurance of the quality of the work. A laser displacement sensor based on optical triangulation of the specular reflection was applied to in-process form measurement of workpieces to compensate for machining error. To separate the motion error of a machining tool from the form measurement of the workpiece, a method for compensating for systematic error due to tilting of the work surface was proposed [28]. Two laser displacement sensors were used for in-situ compensation; one was used for measuring the machined work surface, and the other for measuring the reference surface such as an optical flat.

Plot [e] in **Fig. 5**, "Form measurement of works by contact probe/stylus," includes the touch trigger probe, which is commercialized and widely used in the industry for in-

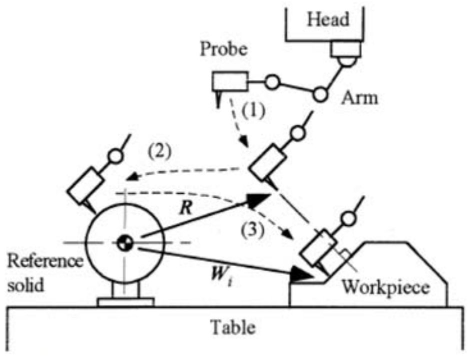
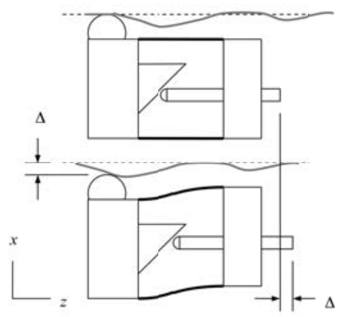
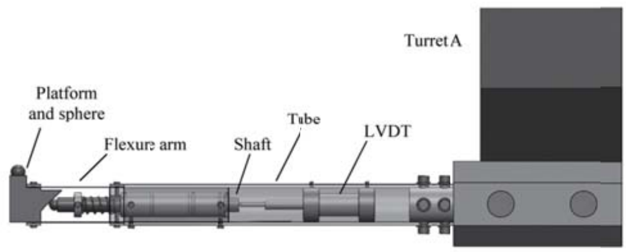


Fig. 9. Multiple-degrees-of-freedom arm for on-machine measurement system [29].

specting workpieces on machine tools during normal and precision machining. The probes are spindle-mounted on the machining centers and turret-mounted on the lathes, and can be used for in-cycle gauging and first-off inspection. The probing eliminates the need for manual process setting, such as tool setting, and part setup. To enable probing to measure the shapes of both the workpiece and the tool during an electrical discharge machining process, a multiple degrees of freedom arm for holding the probe was developed with passive joints, as shown in **Fig. 9** [29]. The potentiality of this technique can be applied to on-machine measurement of a machined workpiece with a complex shape using multiaxis machine tools. As a unique contact measuring method using a feeler, a high-speed on-machine lathe system for measuring deep-holes was developed [30]. The system consists of a laser interferometer set behind the head stock, and a measurement unit with a pentaprism and corner cube prism. The stylus can be used with high accuracy to measure the displacement of a feeler fixed to the tip of the stylus as the displacement of the corner cube prism. The measurement unit is inserted into the inner hole and fed along the hole by rotation. The accuracy of a hole of diameter 63 mm and length 250 mm can be evaluated in 25 min with an accuracy on the order of micrometers. Specialized contact probes were developed to measure the length and bore concentricity of cylindrical extruded tool joints while clamped in a production lathe spindle [31]. A concentricity probe for on-machine probing of extruded tool joints was designed, as shown in **Fig. 10**. The characteristic design concept, wherein an x displacement of the platform caused by variation in the surface location is transferred to the z direction via the 45. surface (nominally a one-to-one ratio), is illustrated in **Fig. 10(a)**. Using this principle, the concentricity probe was developed, as shown in **Fig. 10(b)**. The flexure platform carries a stainless steel sphere that provides contact with the bore surface. As the part rotates, the radial variation of the surface location deflects the platform in the x direction. This motion is transferred to the z axis and detected by a linear variable differential transformer (LVDT). The current demand for small-curvature aspherical optical parts requires an ultra-precision probing method because in-



(a) One-to-one ratio between x direction surface location and z direction shaft motion.



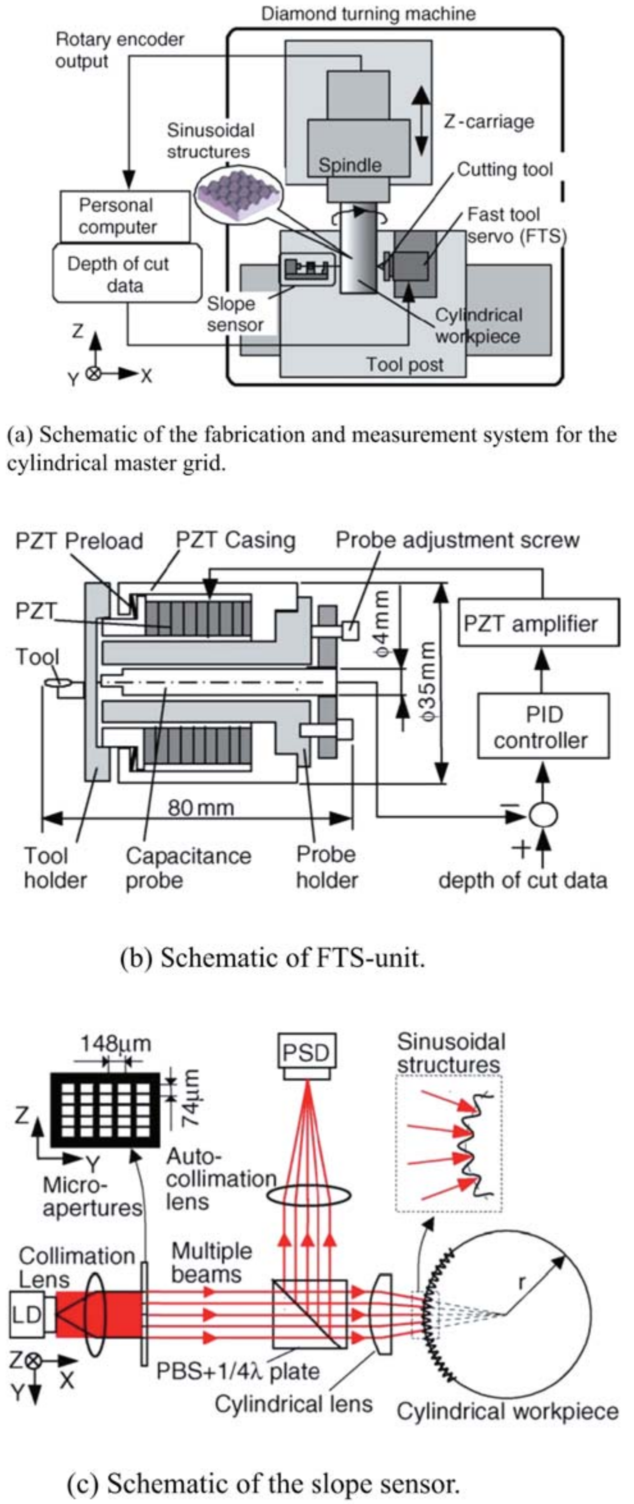
(b) Concentricity probe design.

Fig. 10. Concentricity probe for on-machine probing of extruded tool joints [31].

terferometric methods are inadequate for measuring such steep-angle surfaces. Hence, the development of an ultra-precision on-machine aspherical measurement system is urgently required. To evaluate the aspherical surface of a lens mold on an ultra-precision machine tool, the constant contact angle scanning method using a probe was investigated [32].

The scanning probe method based on measurement difference is usually used to evaluate the straightness profile of a workpiece and/or the straightness motion error of the scanning stage. A fundamental study of measurement algorithms that can exactly reconstruct the straightness profile of workpieces for on-machine measurement is suggested in plot [f] in **Fig. 5**, "New two-point or three-point method for straightness profile measurement of workpieces." New frequency-domain [33] and time-domain [34] methods that can be applied to the measurement of straightness profiles using two or three displacement probes have been developed.

In addition to shape measurement in ultra-precision machining processes, and considering that three-dimensional micro- and nano-structured surfaces can be produced using ultra-precision machine tools, there has been increased need for the in-process and on-machine surface profile measurements shown in plot [g] in **Fig. 5**, "Surface roughness/micro-structured surface measurement of works." For example, a surface encoder for measuring planar motions of precision $X-Y$ stages is required. To realize such an encoder, the fabrication and measurement of a sinusoidal micro-structured surface on an ultra-precision diamond turning machine were attempted as sown in **Fig. 11** [35]. The fabrication and measurement system for the cylindrical master grid (**Fig. 11(a)**) consists of a fast tool servo (**Fig. 11(b)**)

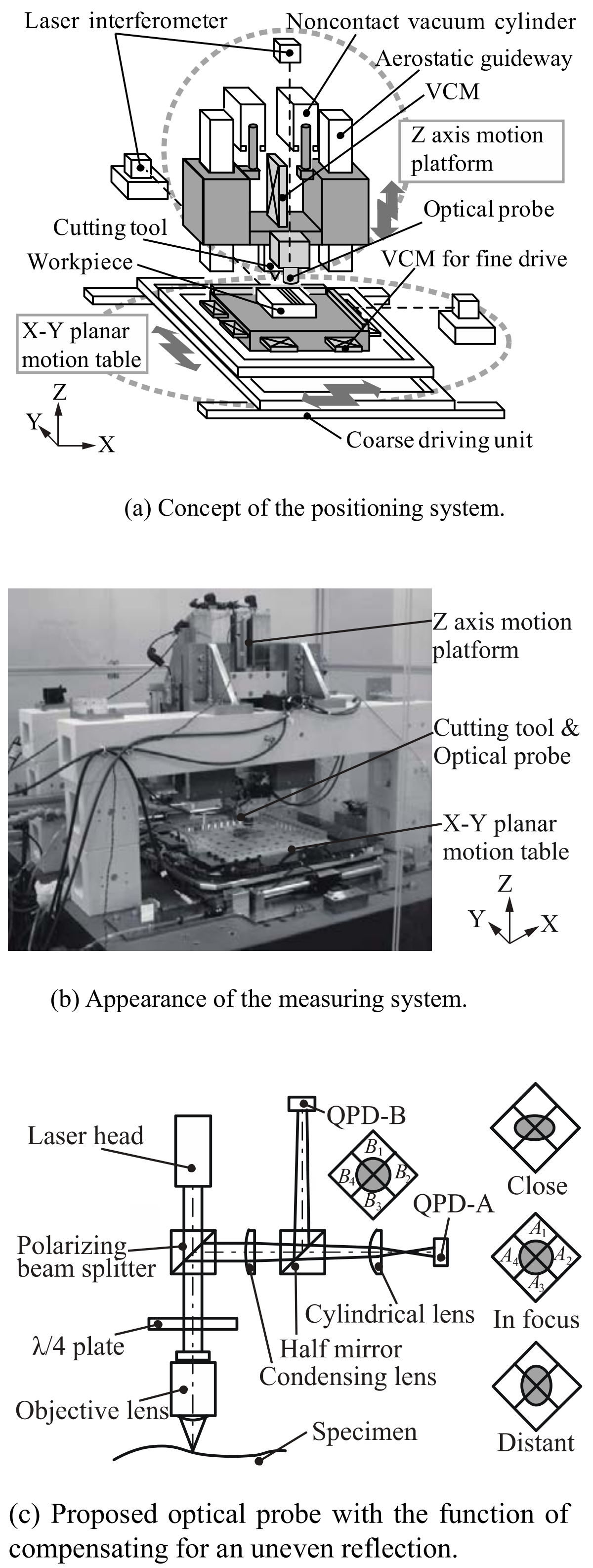


(a) Schematic of the fabrication and measurement system for the cylindrical master grid.

(b) Schematic of FTS-unit.

(c) Schematic of the slope sensor.

Fig. 11. On-machine measurement of cylindrical surface using optical slope sensor [35].



(a) Concept of the positioning system.

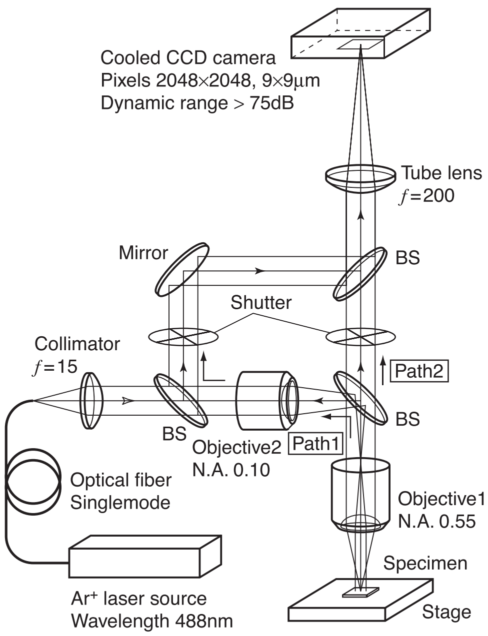
(b) Appearance of the measuring system.

(c) Proposed optical probe with the function of compensating for an uneven reflection.

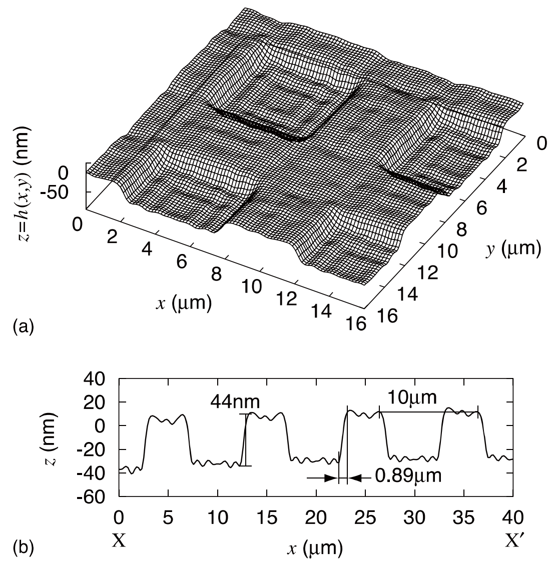
Fig. 12. On-machine optical surface profile measurement for nanomachining [36].

mounted on the tool post of a diamond turning machine and a slope sensor based on the principle of autocollimation (**Fig. 11(c)**). The system is sufficiently practical for reducing the error component caused by the round nose geometry of the tool (10.1 nm to 1.8 nm height amplitude) by compensation based on the measurements of the slope sensor. A systematic design concept of a nanomachining tool with an on-machine measuring function has been proposed. **Fig. 12** shows the developed on-machine system for measuring surface profile for nanomachining with nanometer-scale resolution and measuring range of several hundreds of millimeters [36]. As can be seen in **Fig. 12(a)**, a machining function and a measuring function can be exchanged using a common coordinate system. The $X - Y$ planar motion table system can simultaneously achieve nanometer-scale positioning using voice coil motors (VCMs) for its fine drive mechanism, and high tracking accuracy over large travel distances. The optical probe is driven by a piezoelectric actuator on the Z axis motion platform. The system is shown in **Fig. 12(b)**. The measuring principle of the proposed optical probe is illustrated in **Fig. 12(c)**. An astigmatic focus error detection method is applied in the optical probe. Moreover, the QPD-B is used to compensate for the effect of uneven reflection by the surface. A surface profile can be obtained by scanning the probe using the stage system.

As an application to assessing the finishing process on a machine tool, a noncontact optical sensor is used to achieve in situ measurement of surface roughness on a five-axis milling center that includes milling and polishing [37]. The sensor that was considered for evaluating surface topography employed chromatic confocal sensing technology. Jiang et al. [38] investigated the feasibility of a new type of full-field measurement method to replace electro-mechanical scanning by white-light interferometry for in situ surface roughness measurement. The optical principles of near common-path optical fiber interferometers are based on measurement of the phase shift of the light reflected by the surface using a combination of wavelength division multiplexing techniques, which afford phase-to-depth detection. The proposed method was part of an attempt to create a compact system that is fast, robust, and suitable for in situ surface measurement. Nanometer-precision surface measurement results have been obtained for micro-scale structured samples. Moreover, a fundamental approach to developing a new optical measurement principle for a microstructured surface for in-process measurement was also proposed. The measurement principle was based on optical spectral analysis and the phase retrieval technique. **Fig. 13** shows the developed three-dimensional optical profilometer based on the phase retrieval technique, which is appropriate for in-process measurement of microstructured surfaces [39]. Spectral information about the surface profile is obtained by measuring the Fraunhofer diffraction intensity using the optical system indicated in **Fig. 13(a)**. Because the work surface is illuminated by a Gaussian beam whose waist coincides with the surface, precise positioning of the work is not required. The surface profile within the whole illuminated area can be simultaneously measured without imposition of a scanning process, as illustrated in the sample measured surface profile in **Fig. 13(b)**. A long work distance is achievable without contact with the workpiece surface. The measurements of the diffraction intensity are not likely to be affected by the vibration of the workpiece surface.



(a) The optical configuration of the developed instruments.

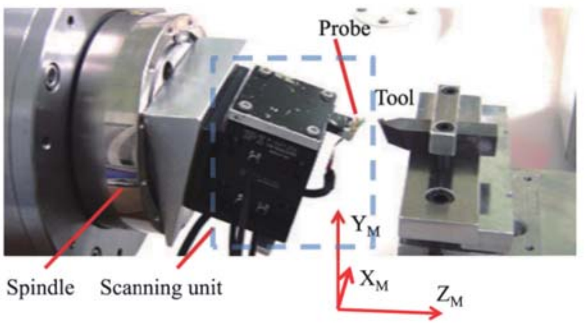


(b) Surface of a reference standard reconstructed by phase retrieval

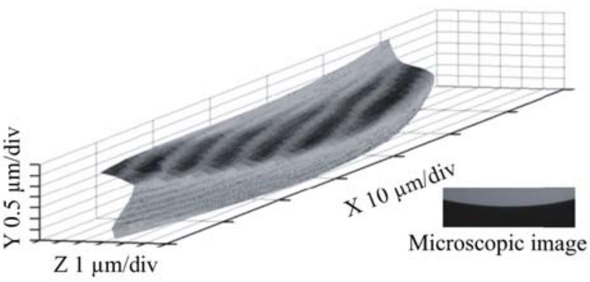
Fig. 13. Optical three-dimensional profilometer for in-process measurement based on phase retrieval technique [39].

4.3. Measurement Tools for Process Condition and Tool Setting

Machining accuracy is affected by the tool conditions including the geometrical features of the tool, tool setting, and tool behavior during direct machine running. Although it is difficult to distinguish the sources of systematic machining error from that of accidental machining error, roughly speaking, systematic machining error is caused by the geometrical features of a tool and the tool setting, whereas accidental machining error is due to the tool behavior during machine running. The specific

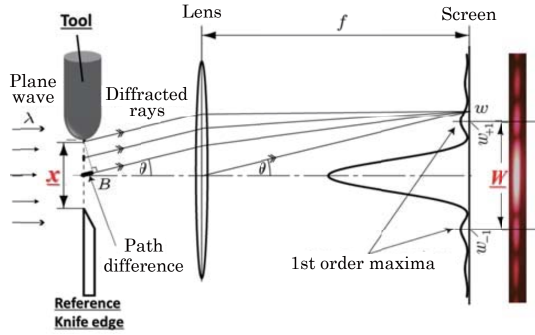


(a) The on-machine measurement setup.

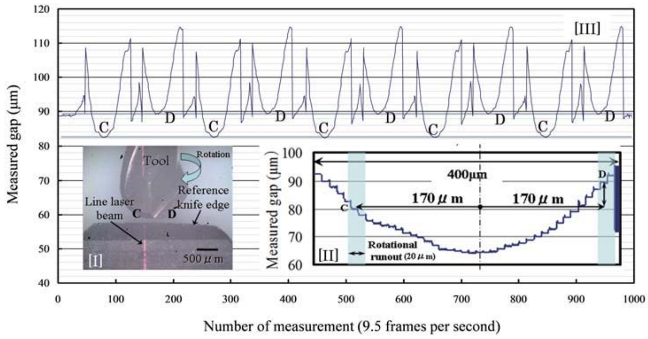


(b) The measurement result of 3D profile of a tool.

Fig. 14. On-machine measurement of tool cutting edge profile [40].



(a) Schematic of diffraction gauge method.

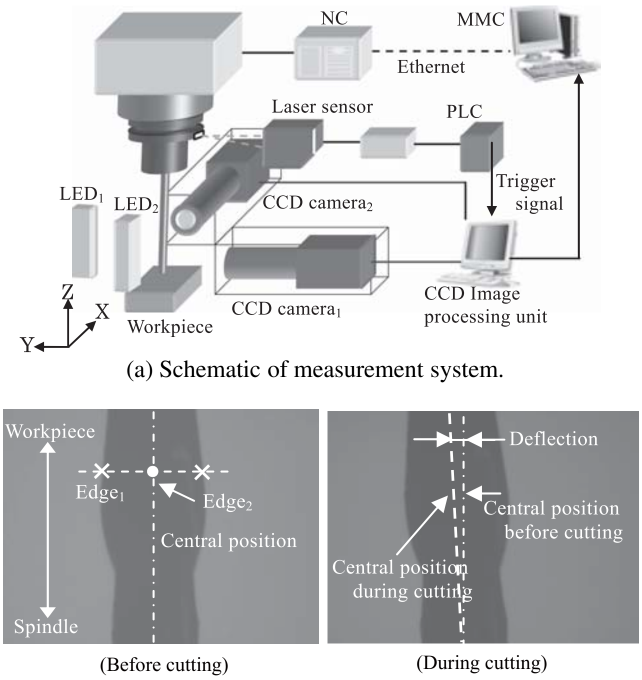


(b) Tool edge monitoring during tool rotation.

Fig. 15. Tool cutting edge monitoring using laser diffraction method [42].

geometrical tool conditions related to systematic machining error are the tool length, tool diameter, cutting edge sharpness, and tool setting with respect to the position of the tool tip and the dynamic balance. However, unexpected behavior and fluctuation of the tool such as deflection and dynamic and thermal conditions, and tool wear during machining make the machining conditions unstable, resulting in accidental machining error. Aided by in-process and on-machine measurements, which make is possible to reduce machining errors due to tool conditions, an essential control of machining process capability can be achieved by improving the machining repeatability.

Based on the coping principle, a cutting edge profile is expected to maintain the same profile during machining, ideally for stable and high machining accuracy. Therefore, the demand for plot [*h*] in **Fig. 5**, "Measurement of cutting edge profile of tools/grinding wheel wear," is inevitable. It is particularly obvious during ultra-precision cutting that the tool cutting edge profile is an essential factor that significantly affects the machining process capability index because the depth of cut must be controlled to within nanometers. It is thus important for assurance of the machined surface quality to make periodic checks on the tool cutting edge under on-machine conditions without removing the tool from the machine. A measuring system based on the atomic force microscope (AFM) (see **Fig. 14**) was developed for measuring the cutting edges of diamond cutting tools on an ultra-precision diamond turning machine [40, 41]. **Fig. 14(a)** shows the on-machine measurement setup, which consists of a scanning system attached to the spindle and the tool mounted on the $X-Y$ slides. When there is mechanical vibration, the three-dimensional profile of the cutting edge is obtained, as shown in **Fig. 14(b)**, where the cyclic error component can be observed. In-process and on-machine measurements of a tool cutting edge profile are required for fine machining using a micro-end mill. This is also because a slight wear of the cutting edge cannot be neglected compared to its diameter. With the aim of evaluating tool wear on the order of several tens of nanometers, an optical measurement technique based on the laser diffraction gauge method was investigated, as shown in **Fig. 15** [42]. The measurement principle is explained in **Fig. 15(a)**. The tool to be measured is brought in close proximity with the reference knife edge to create a narrow edge gap between the tool edge and the reference knife edge. A line laser beam is then illuminated on the edge gap to create a light diffraction pattern. The distance between the maxima peaks in the diffraction pattern is used to scale the measured tool edge. As an example of dynamic measurement results, **Fig. 15(b)** shows the monitoring of the tool cutting edge during rotation of the toll, which suggests the practicality of the method for on-machine measurement. In the case of wet grinding such as in high-precision machining, the wear of the grinding wheel is a machining error factor. In-process measurement of the grinding wheel wear is therefore required. A method for measuring the in-process grinding wheel wear using the hydrodynamic pressure generated in the gap between the grinding wheel and the workpiece during wet grinding has been devel-



(a) Schematic of measurement system.

(b) Tool projection images.

Fig. 16. Two-dimensional monitoring system for tool behavior in end milling using small-diameter tool [46].

oped [43]. The wear of the grinding wheel is compensated for during the grinding process.

Plot [*i*] in **Fig. 5**, "Measurement of tool properties such as cutting force and deflection for machining error analysis," shows that the reduction of accidental machining error by monitoring and measuring the dynamical conditions of the tool, such as the tool deflection and cutting force, is an important technical issue, especially for a microtool. Measurement of the cutting force by measuring the tool deflection by means of image processing [44] and an Eddy-current sensor [45] has been performed. Specifically, a two-dimensional system for monitoring end milling was developed, which is applicable to a small-diameter tool with high-speed rotation as illustrated in **Fig. 16** [46]. The system contains two high-speed CCD cameras for measuring the tool deflection and cutting force in the feed direction and orthogonal direction during machine running, as shown in **Fig. 16(a)**. Projection images of the tool before and during the cutting illustrated in **Fig. 16(b)** were processed to estimate the tool deflection. This system enables in-process monitoring of the tool deflection and measurement of the cutting force.

Plot [*j*] in **Fig. 5**, "Measurement of tool tip position, length, and diameter for effective tool settings," shows emerging technologies for commercialized measuring instruments [47] and measuring instruments developed for industrial use [48, 49]. All the measuring instruments employ an image processing method using CCD cameras and are usable in a machining environment. The commercialized measuring instruments enable the measurement of the tool length, diameter, and tip position of an end mill rotating at 80,000 rpm.

4.4. Fusion Technology for Measurement, Machining, and Process Monitoring

The process capability is evaluated as being worse than the actual process capability when a measuring instrument with measurement uncertainty, as shown in **Fig. 1** is used. Therefore, when improvement of process capability is attempted, the measurement uncertainty should be suppressed to determine the control target based on process capability indices estimated as accurately as possible. However, it is not sufficient to simply manage measurement uncertainty. It is important to enable further fine-tuning of the control quantities during the machining process for high repeatability and robustness. To achieve this progress in machining tools, a fusion of machining and measuring technologies is required to optimize the assessment and control of the machining process during machine running. Therefore, the in-process and on-machine measurements that cannot be clearly defined when measuring an object are shown in the hatched area of **Fig. 5**.

In most studies and developments of in-process and on-machine measurement, the measuring instruments were implemented or mounted external to the machine tool. However, to develop more advanced methods for direct control of the machining process, machine tools with internal sensing devices/measuring instruments were investigated. Plot [*k*] in **Fig. 5**, "Direct measurement of machining force using a sensor built into machine tool," includes conventional studies on machining process monitoring and control using internal/built-in sensors. The sensing/measuring techniques for monitoring and controlling the machining force can be considered as in-process measurements that are independent of external and internal factors. According to Matsubara et al. [50], who comprehensively reviewed schemes for monitoring and controlling cutting forces and torques using external/internal sensors, much research effort has gone into the autonomous determination of machining parameters for conducting feedback control while minimizing human intervention. This was developed to enable even a non-expert machine operator to perform highly productive and accurate machining processes. This is because, in conventional numerically-controlled machining, the process control of an expert machine operator can be provided as feedback control that includes the decisions of the human operator. Furthermore, it is suggested that the application of process monitoring and control to specific machining problems has practical values, which include micromachining and machining of new and difficult-to-cut materials areas in which even expert human operators find effective process planning difficult. This productive insight was supported by the recent development of a spindle with a built-in sensor for microdrilling, which enables simultaneous measurement of the thrust and torque as illustrated in **Fig. 17** [51]. The internal structure of the spindle and the structure of the torque sensor, which comprises electrostatic capacitance sensors, are shown in **Figs. 17(a)** and **(b)**, respectively.

Plot [*l*] in **Fig. 5**, "Process monitoring during material

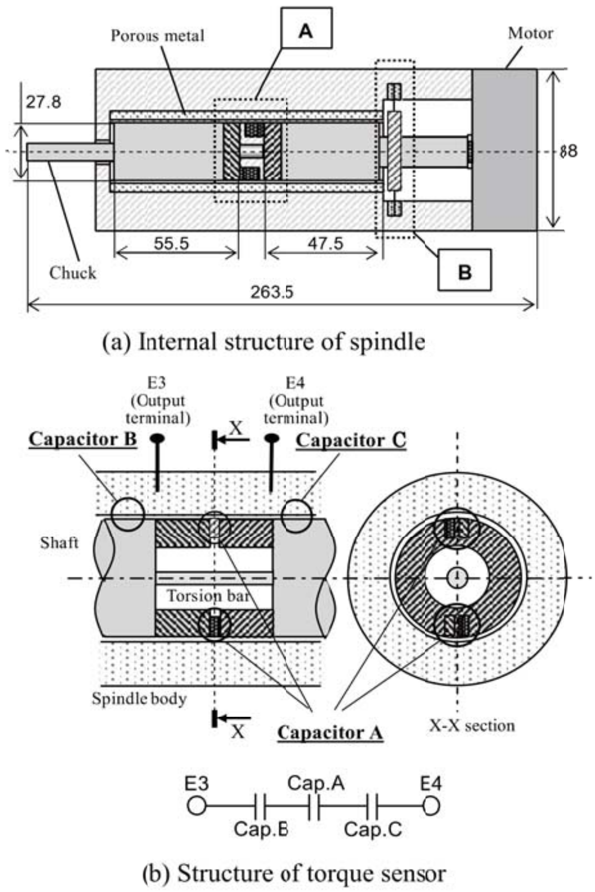


Fig. 17. Built-in-spindle for microdrilling using cutting force detection mechanism [51].

removal," focuses on the very complicated mutual interaction among the control quantities of material removal for process monitoring. For the simultaneous measurement of the grinding force and work form error during cylindrical-plunge grinding, capacitive probes are embedded in the work spindle to produce normal and tangential grinding forces, and an additional capacitive probe is used to measure the size of the workpiece [52]. Measurement results have revealed transient phenomena that occur during grinding. The insight provided by these measurements enable the design of more deterministic processes of grinding and spark-out cycles. The developed monitoring system uses an original microthermo sensor and an AE sensor to detect various machining factors in-process for effective monitoring of ultra-precision machining [53]. The microthermo sensor is directly mounted on the tool rake face. In this system, the two sensors mutually complement their characteristics. Using this specific property, five feature parameters, including the cutting temperature, temperature change rate, temperature signal deviation, and peak AE signal frequency were defined for monitoring, and calculated using periodically segmented data. Particularly, based on understanding of the performance of the material removal processes and resultant workpiece quality, the measurement of the temperature during material removal has been comprehensively reviewed [54]. A well-known material removal phenomenon is the generation of residual stress in the material by the cutting forces, which may result in geometric deviations in subsequent phases of the production process. To measure the relative geometric deviations of the clamped workpiece during the turning process, a water-coupled ultrasound system for the in-process measurement of the distortions of a thin-walled work (i.e., a ring) has been developed [55]. For in-process closed-loop control using a fast tool servo, the actual cutting depth is adjusted based on the in-process measurement of the actual geometric changes.

Finally, new approaches for constructing a fine surface machining system based on in-process and on-machine measurements has been attempted as indicated in plot [*m*] in **Fig. 5**, "Measurement-fused machining system." A machining system that uses a diamond tool was developed, which can be used to fabricate sinusoidal profiles and measure both the tool motions and the workpiece profiles during the machining process [56]. The developed system enables the determination of the copying rate by in-process measurement of the tool motions using a laser displacement sensor and an artifact. Moreover, a compact precision nanomachining and measurement system was developed as shown in **Fig. 18** [57]. In the system, two machining functions, namely scratch machining and milling, and the profile measurement function using AFM were implemented. It has been confirmed by various machining tests that a machining resolution on the order of sub-micrometers to several nanometers can be achieved.

5. Concluding Remarks

With increasing sophistication of the techniques of machining tool/machining processes and the demand for greater accuracy and more efficient production methods, there is the need to improve conventional measuring instruments to manage machining process capability. At the same time, the amount of available information on a machined work is increased. The extended measuring process becomes time-consuming because of the higher number of variables to be measured, the measurement procedures, and the complicated work setting. This is especially crucial in recently developed machine tools used for processes such as ultra-precision machining, micro- and nanomachining, and simultaneous multiple-axis control machining. In-process and on-machine measurements constitute the simplest method for achieving high accuracy and small uncertainty values, as well as reducing the measurement procedures. However, the system requires optimal trade-off between machining time and measurement performance. The conventional approaches described in this paper focus on achieving good measurement performance without a clear trade-off, and on the practical benefit of introducing in-process and on-machine measurements.

The combination of multi-sensor technology and multiple measurement strategies is a promising approach for

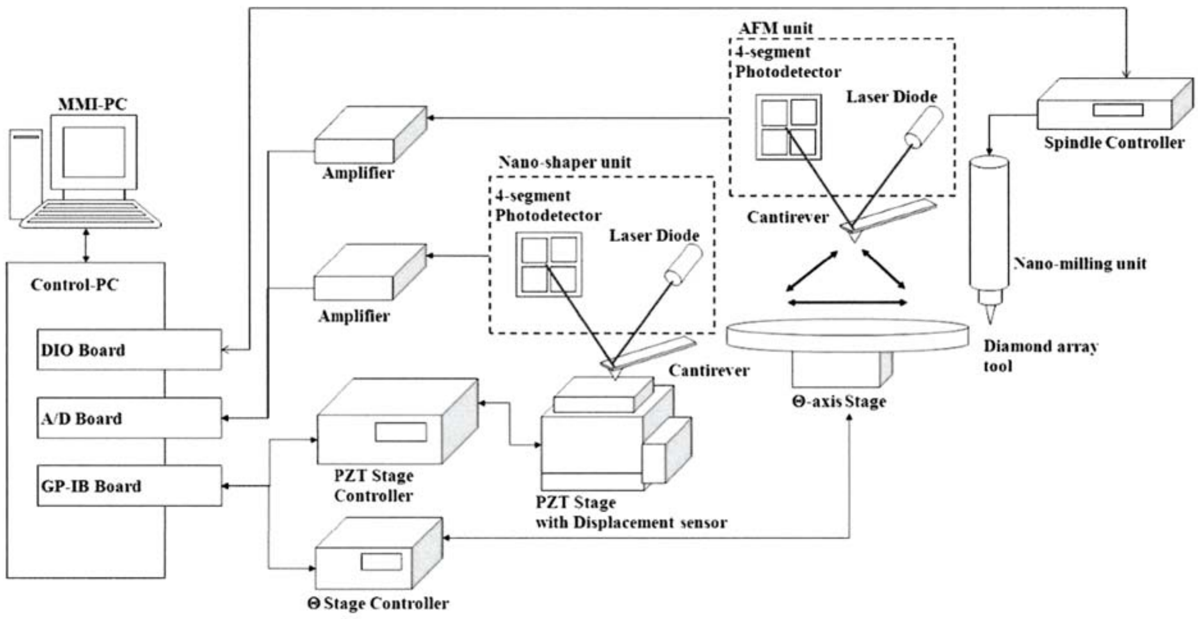


Fig. 18. Schematic of nanomachining center [57].

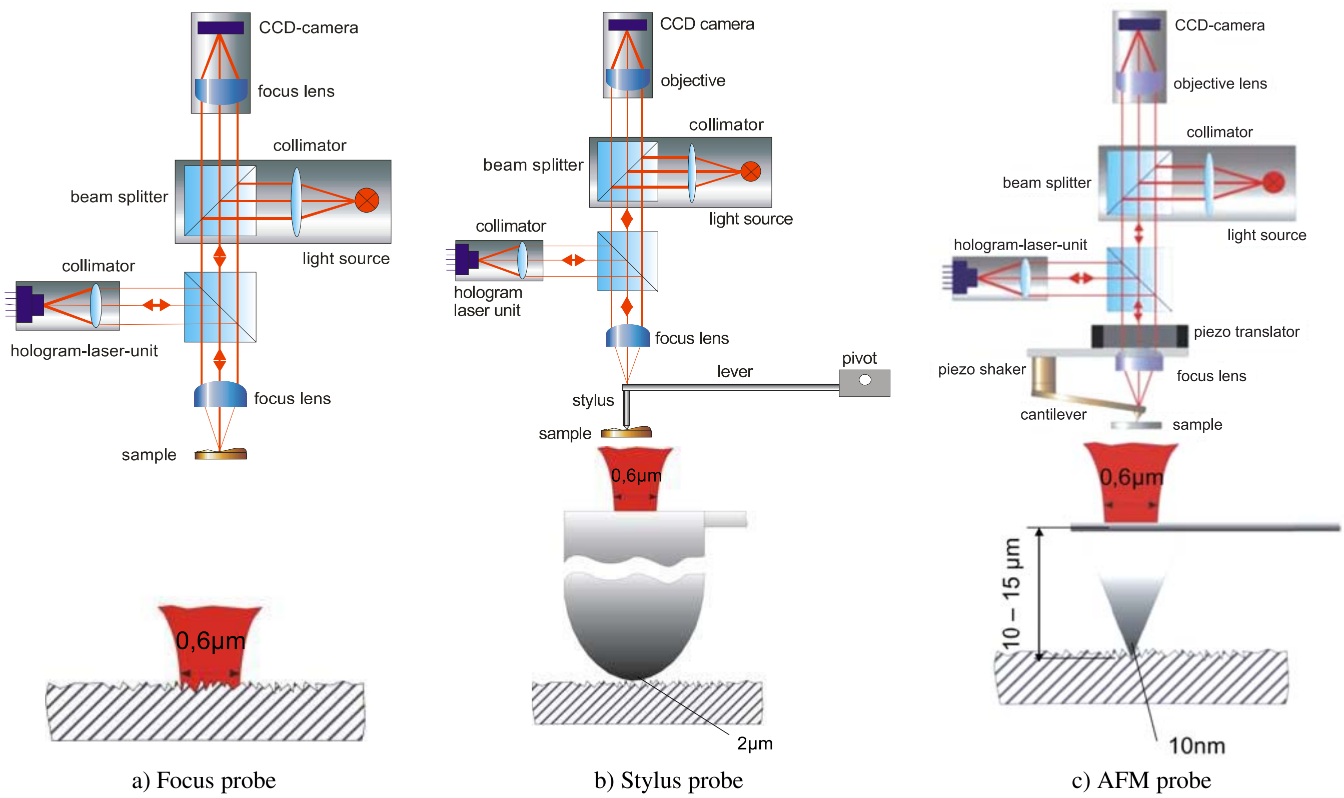


Fig. 19. Multisensor concept consisting of three types of probes [58].

exploring advanced in-process and on-machine measurement techniques. It has the potential to overcome the issue on a trade-off. Such developments are currently available, for example, a multisensor setup for measuring micro- and nanostructures based on a focus sensor, as shown in **Fig. 19** [58], and a multi-probe scanning system comprising three laser interferometers and one autocollimator for measuring a flat bar mirror profile with an accuracy on the order of nanometers [59]. These approaches are advantageous for in-process and on-machine measurement applications for high measurement performance. Large-area analysis and scanning measurement to within a nanometer is only possible by means of multi-sensor technologies and smart multiple measurement strategies.

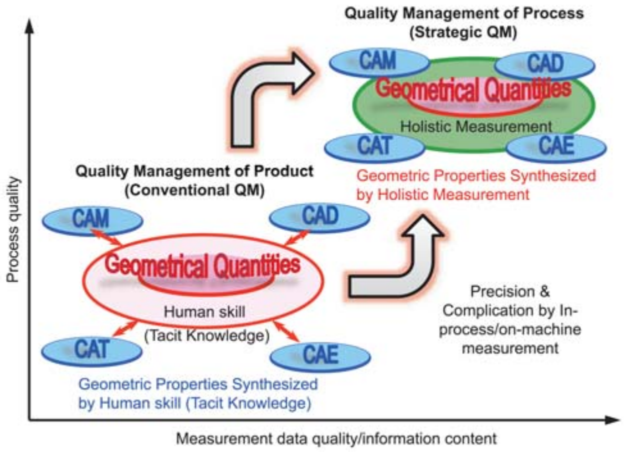


Fig. 20. Process quality management based on in-process/on-machine measurement.

Manufacturing metrology has progressed from being just a support tool in a production system to a comprehensive, strategic, and rapidly progressing tool that provides techniques for fabricating products with more advanced features and higher accuracy. As machining techniques using in-process and on-machine measurement become more intelligent and reliable, holistic measurement techniques (multi-sensor metrology and 100% testing) [60] would be key to strategic QM of processes and products. **Fig. 20** shows the extension of QM from products to processes based on progress in in-process and on-machine measurement techniques. In conventional production systems, CAD, CAM, CAT, and CAE are used for QC depending on human skill; that is, the geometrical properties of a product during production are synthesized by tacit knowledge. However, the integration of CAD/CAM/CAT/CAE with holistic measurement techniques activated by in-process and on-machine measurements will lead to strategic QM, which could be used to realize more creative manufacturing systems with flexible process management. It is inevitable that strategic QM would bring about great advances in in-process and on-machine measurement techniques.

References:

[1] N. Taniguchi, "Current status in, and future trends of, ultraprecision machining and ultrafine materials processing," Annals of CIRP, Vol.32, Issue 2, pp. 573-582, 1983.

[2] M. Shiraishi, "Scope of in-process measurement, monitoring, and control techniques in machining processes – Part 1: In-process techniques for tools," Precision Engineering, Vol.10, No.4, pp. 179-189, 1988.

[3] M. Shiraishi, "Scope of in-process measurement, monitoring, and control techniques in machining processes – Part 2: In-process techniques for workpieces," Precision Engineering, Vol.11, No.1, pp. 27-37, 1989.

[4] M. Shiraishi, "Scope of in-process measurement, monitoring, and control techniques in machining processes – Part 3: In-process techniques for cutting ptocesses and machine tools," Precision Engineering, Vol.11, No.1, pp. 39-47, 1989.

[5] S. Ueno, "On machine measuring system for machine tools," J. of the Japan Society for Precision Engineering, Vol.75, No.11, pp. 1269-1272, 2009. (in Japanese)

[6] ISO 230-10, "Test code for machine tools – Part 10: Determination of the measuring performance of probing systems of numerically controlled machine tools," 2011.

[7] Y. Takaya, "Trend in In-Process & On-Machine Measureemnt," Mechanical Engineering, Vol.60, No.7, pp. 17-23, 2012. (in Japanese)

[8] International Organization for Standardization, "Guide to Expression of Uncertainty of Measurement," JCGM 100, 2008.

[9] A. Weckenmann and M. Rinnagl, "Acceptance of processes: do we need decision rules?" Precision Engineering, Vol.24, pp. 264-269, 2000.

[10] T. Kohno, M. Omoda, Y. Okazaki, N. Ozawa, and K. Mitsui, "In-process measurement and workpiece-refered form accuracy control (1st report) : Concept of the method and preliminary experiment," J. of the Japan Society for Precision Engineering, Vol.54, No.8, pp. 1463-1468, 1988. (in Japanese)

[11] T. Kohno, Y. Okazaki, N. Ozawa, K. Mitsui, and M. Omoda, "In-process measurement and a workpiece-referred form accuracy control system (WORFAC): concept of the method and preliminary experiment," Precision Engineering, Vol.11, No.1, pp. 9-14, 1989.

[12] Y. Uda, T. Kohno, and T. Yazawa, "In-process measurement and a workpiece-referred form accuracy control system (WORFAC): application to cylindrical turning using an ordinary lathe," Precision Engineering, Vol.18, No.1, pp. 50-55, 1996.

[13] T. Yazawa, T. Yamazaki, and T. Kohno, "In-process measurement and workpiece-refered form accuracy control (7th report) : Controlled cutting with reference surface for central part and expansion to periphery," J. of the Japan Society for Precision Engineering, Vol.64, No.11, pp. 1689-1693, 1998. (in Japanese)

[14] S. Ibaraki and W. Knapp, "Indirect Measurement of Volumetric Accuracy for Three-Axis and Five-Axis Machine Tools: A Review," Int. J. of Automation Technology, Vol.6, No.2, pp. 110-124, 2012.

[15] Y. Ihara, "Ball Bar Measurement on Machine Tools with Rotary Axes," Int. J. of Automation Technology, Vol.6, No.2, pp. 180-187, 2012.

[16] S. Ibaraki, Y. Kakino, T. Akai, N. Takayama, I. Yamaji, and K. Ogawa, "Identification of Motion Error Sources on Five-axis Machine Tools by Ball-bar Measurements (1st Report) – Classification of Motion Error Components and Development of the Modified Ball Bar Device (DBB5) –," J. of the Japan Society for Precision Engineering, Vol.76, No.3, pp. 333-337, 2010. (in Japanese)

[17] T. Matsushita and A. Matsubara, "Identification and compensation of geometric errors in five-axis machine tools with a tilting rotary table using conic trajectories measured by double ball bar," J. of the Japan Society for Precision Engineering, Vol.77, No.6, pp. 594-598, 2011. (in Japanese)

[18] S. Aguado, J. Santolaria, D. Samper, and J. J. Aguilar, "Influence of measurement noise and laser arrangement on measurement uncertainty of laser tracker multilateration in machine tool volumetric verification," Precision Engineering, 2013. (in-press)

[19] T. Saiki, M. Tsutsumi, H. Suzuki, M. Kouya, and M. Ushio, "Development of Measurement for Motion Accuracy of 5 Axis NC Machine Tool," Int. J. of Automation Technology, Vol.2, No.2, pp. 111-118, 2008.

[20] E. Trapet, J.-J. Aguilar Martín, J.-A. Yagu, H. Spaan, V. Zelený, "Self-centering probes with parallel kinematics to verify machine-tools," Precision Engineering, Vol.30, pp. 165-179, 2006.

[21] W. Gao, M. Tano, T. Araki, S. Kiyono, and C. H. Park, "Measurement and compensation of error motions of a diamond turning machine," Precision Engineering, Vol.31, pp. 310-316, 2007.

[22] T. Nomura, K. Yoshikawa, H. Tashiro, K. Takeuchi, N. Ozawa, Y. Okazaki, M. Suzuki, F. Kobayashi, and M. Usuki, "On machine shape measurement of workpiece surface with Fizeau interferometer," Precision Engineering, Vol.14, No.3, pp. 155-159, 1992.

[23] T. Nomura, H. Miyashiro, K. Kamiya, K. Yoshikawa, H. Tashiro, M. Suzuki, M. Usuki, and F. Kobayashi, "Shape measurement of workpiece surface with zone-plate interferometer during machine running," Precision Engineering, Vol.15, No.2, pp. 86-92, 1993.

[24] T. Nomura, K. Kamiya, H. Miyashiro, S. Okuda, H. Tashiro, and K. Yoshikawa, "Shape measurement of mirror surfaces with a lateral-shearing interferometer during machine running," Precision Engineering, Vol.22, No.4, pp. 185-189, 1998.

[25] T. Kohno, D. Matsumoto, T. Hosogoe, T. Yazawa, and Y. Uda, "Radial shearing interferometer for on-machine measurement," J. of the Japan Society for Precision Engineering, Vol.65, No.3, pp. 443-446, 1999. (in Japanese)

[26] T. Kohno, T. Yazawa, D. Saito, and S. Kohno, "Figure error control for diamond turning by in-process measurement," Precision Engineering, Vol.29, pp. 391-395, 2005.

[27] C. P. Keferstein, D. Honegger, H. Thurnherr, B. Gschwend, A. L. Cooke1, "Process monitoring in non-circular grinding with optical sensor," Annals of the CIRP, Vol.57, No.1, pp. 533-536, 2008.

[28] Y. Koike, D. Kono, A. Matsubara, and I. Yamaji, "In-situ measurement by using a measurement-fused machining system," J. of the Japan Society for Precision Engineering, Vol.76, No.8, pp. 945-949, 2010. (in Japanese)

[29] K. Furutani, K. Iwamoto, H. Takezawa, and N. Mohri, "Multiple degrees-of-freedom arm with passive joints for on-the-machine measurement system by calibrating with geometric solids," Precision Engineering, Vol.23, pp. 113-125, 1999.

[30] A. Katsuki, H. Onikura, T. Sajima, H. Murakami, T. Sato, T. Caetano, H. M. Ali, and O. Ohnishi, "Study on high-speed on-machine measurement of deep-hole accuracy," J. of the Japan Society for Precision Engineering, Vol.77, No.7, pp. 681-687, 2011. (in Japanese)

[31] A. Graziano, T. L. Schmitz, "Sensor design and evaluation for on-machine probing of extruded tool joints," Precision Engineering, Vol.35, pp. 525-535, 2011.

[32] H. Suzuki, J. Sugawara, M. Kondo, Y. Yamagata, S. Morita, T. Makino, K. Yoshida, and T. Higuchi, "Development of Ultra-Precision On-machine Aspherical Measurement System by Constant Contact Angle Scanning Method," Die and Mold Technology, Vol.24, No.8, pp. 130-131, 2009. (in Japanese)

[33] Y.Zi-qiang, L. Sheng-yi, "Exact straightness reconstruction for on-machine measuring precision workpiece," Precision Engineering, Vol.29, pp. 456-466, 2005.

[34] Y. Zi-qiang, L. Sheng-yi, "High accuracy error separation technique for on-machine measuring straightness," Precision Engineering, Vol.30, pp. 192-200, 2006.

[35] W. Gao, M. Tano, S. Sato, and S. Kiyono, "On-machine measurement of a cylindrical surface with sinusoidal micro-structures by an optical slope sensor," Precision Engineering, Vol.30, pp. 274-279, 2006.

[36] H. Sawano, M. Takahashi, H. Yoshioka, H. Shinno, and K. Mitsui, "On-Machine Optical Surface Profile Measuring System for Nano-Machining," Int. J. of Automation Technology, Vol.5, No.3, pp. 369-376, 2011.

[37] Y. Quinsat and C. Tournier, "In situ non-contact measurements of surface roughness," Precision Engineering, Vol.36, pp. 97-103, 2012.

[38] X. Jiang, "In situ real-time measurement for micro-structured surfaces," Annals of the CIRP, Vol.60, No.1, pp. 563-566, 2011.

[39] A. Taguchi, T. Miyoshi, Y. Takaya, and S. Takahashi, "Optical 3D profilometer for in-process measurement of microsurface based on phase retrieval technique," Precision Engineering, Vol.28, pp. 152-163, 2004.

[40] T. Asai, S. Ferdous, Y. Arai, Y. Yang, and W. Gao, "On-Machine Measurement of Tool Cutting Edge Profiles," Int. J. of Automation Technology, Vol.3, No.4, pp. 408-414, 2009.

[41] T. Asai, Y. Arai, and W. Gao, "A Precision Instrument for 3D Edge Profile Measurement of Single Point Diamond Micro-Cutting Tools," J. of the Japan Society for Precision Engineering, Vol.75, No.7, pp. 892-896, 2009. (in Japanese)

[42] P. Khajornrungruang, K. Kimura, Y. Takaya, and K. Suzuki, "High Precision Tool Cutting Edge Monitoring Using Laser Diffraction for On-Machine Measurement," Int. J. of Automation Technology, Vol.6, No.2, pp. 163-167, 2012.

[43] K. Furutani, N. T. Hieu, N. Ohguro, and T. Nakamura, "Automatic compensation for grinding wheel wear by pressure based in-process measurement in wet grinding," Precision Engineering, Vol.27, pp. 9-13, 2003.

[44] K. Narukawa and T. Kawai, "Development of cutting force measurement technique for milling process with small diameter end mill," J. of the Japan Society for Precision Engineering, Vol.76, No.7, pp. 814-818, 2010. (in Japanese)

[45] K. Kasahara, Y. Tanaka, and A. Hirota, "Analysis of tool deflection and mechanism of surface generation in ball end milling of an inclined surface (2nd Report): – On the properties of machined surface and machining error caused with tool deflection –," J. of the Japan Society for Precision Engineering, Vol.76, No.8, pp. 901-906, 2010. (in Japanese)

[46] S. Yoshimitsu, S. Satonaka, Y. Kawano, D. Zuo, and S. Yamashita, "Two-dimensional monitoring system for tool behavior in end milling with small diameter tool," J. of the Japan Society for Precision Engineering, Vol.77, No.9, pp. 889-894, 2011. (in Japanese)

[47] T. Yamamoto, M. Yauchi, and K. Nagai, "The function of a Tool Measuring Instrument with CCD Camera," J. of Die and Mold Technology, Vol.25, No.12, pp. 26-27, 2010. (in Japanese)

[48] Y. Sato, "Sample Case of High Accuracy Measurement on Machine by Optical Type Tool Measurement System," J. of Die and Mold Technology, Vol.26, No.12, pp. 28-29, 2011. (in Japanese)

[49] Y. Takeyasu, H. Sasaki, M. Mondo, and T. Tsutsumoto, "Stop-motion-monitoring of Rotating Machine Tool using Synchronized Flash Light," J. of Die and Mold Technology, Vol.26, No.12, pp. 30-31, 2011. (in Japanese)

[50] A. Matsubara and S. Ibaraki, "Monitoring and Control of Cutting Forces in Machining Processes: A Review," Int. J. of Automation Technology, Vol.3, No.4, pp. 445-456, 2009.

[51] R. Arai, N. Morita, T. Nishi, Y. Choushu, K. Oguchi, N. Takei, S. Nakayama, and T. Tanaka, "Development of sensor built-in spindle for micro drilling with a detection mechanism of cutting force," J. of the Japan Society for Precision Engineering, Vol.77, No.10, pp. 944-949, 2011. (in Japanese)

[52] E. R. Marsha, A. W. Moerleina, T. R. S. Deakynea, and M. J. VanDoren, "In-process measurement of form error and force in cylindrical-plunge grinding," Precision Engineering, Vol.32, pp. 348-352, 2008.

[53] H. Yoshioka, M. Hayashi, and H. Shinno, "Status Monitoring of Ultraprecision Machining Using Micro Thermo Sensor and AE Sensor," Int. J. of Automation Technology, Vol.3, No.4, pp. 422-427, 2009.

[54] M. A. Davies, T. Ueda, R. M'Saoubi, B. Mullany, and A. L. Cooke1, "On The Measurement of Temperature in Material Removal Processes," Annals of the CIRP, Vol.56, No.2, pp. 581-604, 2007.

[55] D. Stoebener1 and M. Dijkman, "An Ultrasound In-Process-Measuring System to Ensure a Minimum Roundness Deviation for Rings During Turning," Annals of the CIRP, Vol.56, No.1, pp. 513-516, 2007.

[56] D. Kono, A. Matsubara, Y. Koike, and I. Yamaji, "Measurement of the copying rate of tool edge motions by using a measurement-fused machining system," J. of the Japan Society for Precision Engineering, Vol.75, No.4, pp. 520-524, 2009. (in Japanese)

[57] K. Inagaki, N. Morita, K. Ashida, and J. Saito, "Study for development of nano-machining and measurement system of machining center type," J. of the Japan Society for Precision Engineering, Vol.74, No.11, pp. 1176-1181, 2008. (in Japanese)

[58] E. Manske, G. Jager, and T. Hausotte, "Combination of multi sensor technology and multiple measurement strategies in micro- and nanometrology," Proc. of the 10th Int. Symp. on Measurement and Quality Control, pp. D6-075-1, 2010.

[59] P. Yanga, T. Takamura, S. Takahashi, K. Takamasua, O. Sato, S. Osawa, and T. Takatsuji, "Multi-probe scanning system comprising three laser interferometers and one autocollimator for measuring flat bar mirror profile with nanometer accuracy," Precision Engineering, Vol.35, pp. 686-692, 2011.

[60] A. Weckenmann, "The role of metrology in the exchange of goods and in the development of manufacturing technologies," Proc. of the 10th Int. Symp. on Measurement and Quality Control, pp. 1-4, 2010.

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- "Surface analysis of the chemical polishing process using a fullerenol slurry by Raman spectroscopy under surface plasmon excitation," Annals of the CIRP, Vol.62, Issue 1, pp. 571-574, 2013.

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