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Dimensional Metrology for Micro/ Mesoscale Manufacturing

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CONTENTS

15.1 Introduction

Lord Kelvin said, “To measure is to know,” and “If you can not measure it, you can not improve it.” In fact, it is not possible to really know what is manufactured until it is measured. This has been a particular challenge in micro/mesoscale manufacturing because development of production processes has considerably outpaced development of measurement processes. Decisions that need to be made regarding a part or product being manufactured are based on measurements. These cannot be informed decisions if one does not have confidence in, or does not fully understand, the uncertainty of the measurement process.

Several changes have been made to the text for better clarity. Please check and confirm if the edits retain the intended meaning.

This chapter provides an overview of the most common methods used for geometric dimensional metrology in three dimensions (3D) at the micro/mesoscale. The references provided in this chapter provide examples of the work in the area, and not an exhaustive list. A similar study focusing on academic pursuits in the area can be found elsewhere, with no fewer than 175 references [1]. The processes discussed here are by no means an exhaustive list of all measurement processes used for micro/mesoscale metrology. However, they are the processes used most frequently; they all have multiple commercially available systems that measure the 3D topography of the surface of the part under test. The strengths, limitations, and challenges of each method are presented. The methods are grouped into three categories, touch probe, optical measurement, and scanning probe microscopy (SPM). To properly frame this discussion, we start by defining the scale being investigated, then introduce the concept of measurement uncertainty, and finally discuss some general considerations that need to be made for all measurement methods.

15.1. Defining the Scale

We have cited reference 2 here. Please confirm whether this is okay.

For the purposes of the current discussion, the micro/mesoscale is defined as ranging from 1 μm to 50 mm. Most parts manufactured at the micro/mesoscale have overall sizes ranging above 100 μm. However, designed features on these parts can be as small as tens of micrometers and the tolerances of such features can be close to 1 μm [1, 2]. Figure 15.1 shows a variety of measurement processes that fit within this size range.

15.1.2 Uncertainty

Just as no part can be made perfectly, no measurement can be made perfectly. Uncertainty is both the concept and the quantity that expresses the amount of doubt in a particular measurement. The formal definition of uncertainty (of a measurement) in the *International Vocabulary of Basic and General Terms in Metrology* (*VIM*) is a "non-negative parameter characterizing the dispersion of the quantity values being attributed to the measurand, based

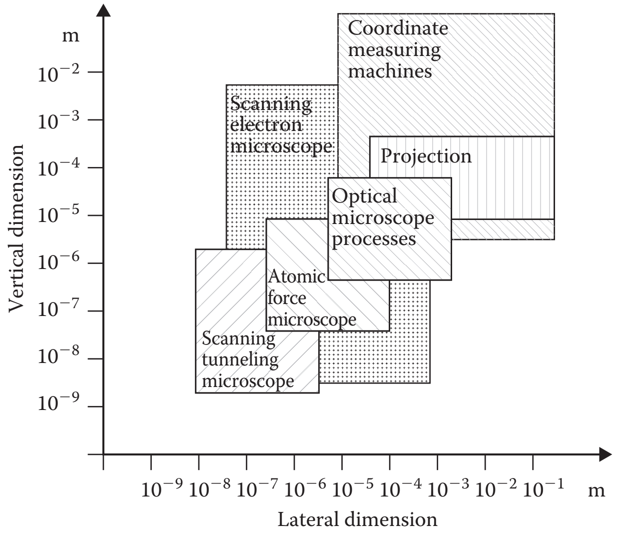

FIGURE 15.1
Size scale of typical measurement techniques employed at the micro/mesoscale. Acronyms are described in the text. (From Hansen et al., *CIRP Annals*, 55(2), 721–743, 2006 and Weckenmann, A. and Ernst, R., *Technisches Messen*, 7–8, 334–342, 2000.)

on information used" [3]. A general procedure for calculating measurement uncertainty is described in the *Guide to the Expression of Uncertainty in Measurement* (GUM) [4].

In general, the uncertainty of a measurement is due to various sources. For example, a measurement of distance is influenced by the device used to measure it, the environment in which it is measured, the setup of the measurement components, and the number and positions of samples collected. Uncertainty in any of these inputs contributes to uncertainty of the overall measurement. How measurement uncertainty affects acceptance or rejection of a part based on geometric dimensioning and tolerancing (GD&T) is governed by standards [5].

Measurement uncertainty encompasses many traditional concepts in measurement including resolution, accuracy, and repeatability. Care should be taken when investigating device specification sheets that terminology is used properly. For example, most specification sheets provide a number associated with the "accuracy" of the device. However, the VIM defines accuracy as "closeness of the agreement between the result of a measurement and a true value of the measurand," and states that "accuracy" is a qualitative concept that cannot be quantified. Therefore, the term *accuracy* on data sheets often refers to the uncertainty associated with the device, but can also be more in line with resolution or repeatability. This chapter focuses on the factors that contribute to the uncertainty in the measurement device.

15.1.3 Environment

The environment in which a measurement is made can greatly influence the measurement, especially at the micro/mesoscale. Specific influences on specific measurement methods are discussed later in more detail. However, to minimize measurement uncertainty, some general considerations that apply to all measurements should be made. Vibration isolation of the part being measured, the device used for measurement, and the room in which the measurement is taking place should all be considered. Temperature can have a large effect on measurement results. All components of a measurement, including the measurement device and the part being measured, can expand or contract (depending on their coefficients of thermal expansion) as a result of a change in their temperature. The temperature in the environment directly affects the temperatures of the device and the part. For example, a part measured at one temperature will have a different size when transferred to an environment with a different temperature because of thermal expansion/contraction. Most standards and best practices recommend calibrating devices and performing measurements at 20°C. In addition to the actual temperature, the stability of the temperature and the uncertainty of temperature measurement are also of concern.

15.1.4 Unique Challenges

Many people expect that as a part scales down in size, its tolerances will also scale down. However, this is generally not the case. It is common for parts on the traditional scale to have dimensions on the order of 100 mm with tolerances in the range of 25 μm. However, a part 100 times smaller (1 mm dimension) will rarely have a tolerance 100 times smaller (0.25 μm) because of the difficulty not only in producing a part with that tolerance but also in verifying that the desired tolerance is achieved.

Consider the rule of ten. A general rule of thumb is that to measure a feature with a specified tolerance, the uncertainty associated with the measurement device should be at least 10 times smaller than the tolerance. It is common for micro/mesoscale parts as large as tens of millimeters to have tolerances close to 1 µm. Thus, in order to measure this part following the rule of ten, the measurement device must have an uncertainty less than 100 nm over a range of tens of millimeters, a ratio of 10^5. Although devices with such a scale do exist, they are often very specialized and expensive. Therefore, the rule of ten, considered by many metrologists to be overkill, is often relaxed at the micro/mesoscale. A better guideline endorsed by standards [5] is a ratio of 4:1.

15.1.5 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) of micro/mesoscale parts is often found in literature. Electron microscopy is similar to light or optical microscopy except that to achieve better resolution and depth of focus, an electron source is used instead of light for illumination. In SEM, a focused beam of high-energy electrons is rastered over a sample surface in two dimensions. The interaction of the electron beam with the sample surface results in secondary electrons being emitted from the surface. These secondary electrons are collected by a detector and converted into an image of the sample surface [6].

SEM is an excellent tool for imaging and qualitatively assessing small parts because of the excellent resolution and high depth of focus achievable. However, this method is generally not well suited to 3D measurement. Because of the high depth of focus and the fact that the electron beam is only scanned in one plane, it is difficult to interpret the height of features imaged under SEM. In addition, low-uncertainty measurement would require the microscope to be calibrated at every magnification and every setting. Microscopy settings (such as magnification, spot size, and astigmation) are continually changed to improve image quality, and the magnetic microscope "lenses" tend to drift. Thus, an SEM continually needs recalibration to perform low-uncertainty dimensional measurements. SEM may be well suited to certain 1D measurements (e.g., line width) and 2D measurements, but care should be taken that in addition to proper calibration, the feature being measured should be truly normal to the detector. 3D measurement by SEM would require multiple images or beams (stereo pairs), and such systems continue to be developed.

15.2 Touch Probe Measurement

Touch probe measurement is a logical place to start the examination of micro/mesoscale dimensional metrology methods because the method is extremely powerful and very well understood at the traditional scale. Coordinate measuring machines (CMMs) provide low uncertainty postprocess 3D measurements of traditional-scale parts. In addition, many new traditional-scale machine tools come equipped with spindle-mounted touch probes both for workpiece setting and for part dimensional measurement. A considerable amount of effort has gone into characterizing the coordinate measuring process, as evidenced by an entire book written about the method [7] and by the 208 references in a review paper on the subject [8]. The micro/mesoscale process is not dramatically different from the traditional-scale process. The range of the measurement is limited only by the places the probe can reach, so the output of point coordinates is a true 3D measurement. There is considerable effort going into enabling CMMs to operate on the micro/mesoscale [9–17].

However, significant obstacles still remain in micro/mesoscale measurement by a touch probe. The most significant of these is the size of the probe itself. A touch probe cannot

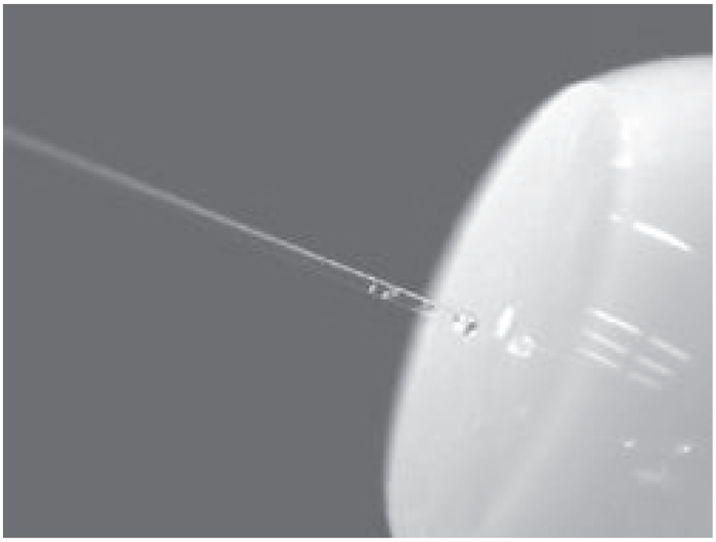

FIGURE 15.2
Fiber probe entering a 125-μm hole.

measure an internal feature (such as bore, slot, and hole) if the probe cannot fit inside the feature. While this concept is obvious to many, it is still a significant hurdle because probes smaller than 25 μm in diameter are rare, but micro/mesoscale features of that size are becoming common (Figure 15.2). Adding to the problem is the fact that even as smaller probes become more available, uncertainty in the calibration of the probe tip profile becomes more important and more troublesome [12]. Also to be considered is an averaging effect due to the relative size of the probe tip to the size of the feature being measured.

At the much smaller size scales of micro/mesoscale manufacturing, electrostatic, Van der Waals, and meniscus forces play a much larger role, affecting touch probe measurement. These forces cause the probe to stick to the surface after initial contact. More importantly, small, less stiff probes can be pulled toward the surface or in undesirable directions, resulting in increased measurement uncertainty (Figure 15.3) and possible damage to the small, often fragile probes. A good deal of research has led to some unique solutions in this area, and modern CMMs designed specifically for the micro/mesoscale often use vibrating probes to break the contact at the surface [9, 15–17]. As a vibrating probe approaches a surface, a change in vibration amplitude or frequency can signal contact. However, vibrating the probe greatly increases the effective tip diameter because the surface detection point is governed not only by the physical size of the probe but also by the amplitude of the vibration (Figure 15.4).

The size scales of mesoscale machine tools and micro/mesoscale parts lead to additional complications. Contact detection is more important at the micro/mesoscale because contact areas are so small that local stresses can be rather large. In fact, contact by a 100-μm sphere can leave a permanent indentation in an aluminum surface at forces as low as 500 μN. Thus, keeping contact forces low and quickly detecting the probe contact is highly important, but at the same time, more difficult. Several studies focus entirely on this problem [10–12].

The uncertainty of CMMs is well understood and is a function of several components [18]. Contributing to the combined uncertainty of a measurement are the uncertainty in the machine positioning, uncertainty in the probing system, the sampling of coordinates

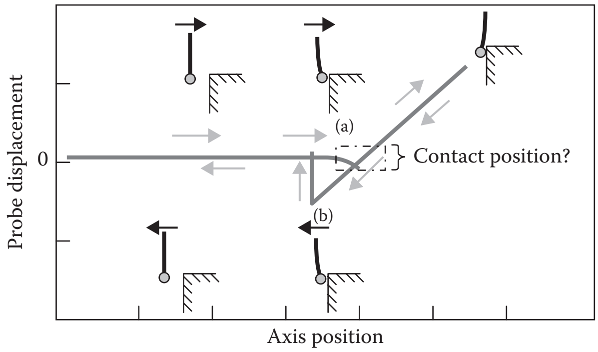

FIGURE 15.3
As a microscale touch probe approaches a surface, forces can draw the probe tip toward the surface (a) and can cause the probe tip to adhere to the surface as the probe retracts (b). These phenomena can result in an increase in uncertainty of measuring the surface's position.

Should we retain the "?" appearing after "contact position" in the artwork of Figure 15.3?

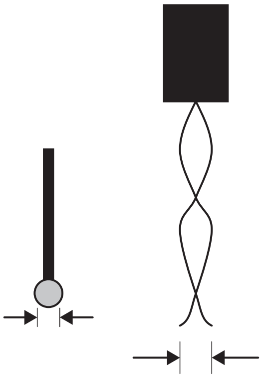

FIGURE 15.4
Apparent probe diameter differs greatly with traditional probes and vibrating probes. With traditional probes, the apparent diameter is slightly smaller than sphere diameter owing to time delay in triggering. With vibrating probes, the apparent diameter is more a function of the vibration amplitude.

(the number and distribution of coordinates measured on the part), and uncertainty in the fitting of geometric shapes to the sampled coordinates. National and international standards govern the determination of machine and probing system uncertainty components [19,20]. Some recent work has focused on qualification and verification tests and standards for micro/mesoscale-specific systems [21]. Modern CMMs provide excellent positioning accuracy, and their positioning errors are also well mapped, allowing for compensation. Uncertainty in the probing system is a function of the probe tip profile and the sensitivity of the triggering mechanism. Under proper conditions, uncertainty in dimensional measurements using CMMs can be as small as tens of nanometers [15].

CMM measurement requires a high degree of environmental control and is rather slow. Because contact is required for measurement, a thin layer of water on the surface can affect measurement. Therefore, a high level of humidity control is required along with temperature control and vibration isolation. Individual part coordinates are measured in series, and measuring hundreds of coordinates to reduce sampling and fitting uncertainties can take hours. The number of points still pales in comparison to the number of points used in optical processes that can collect millions of points in a matter of seconds.

15.3.1 Optical Measurements

Review papers [22,23] discussing optical methods for dimensional metrology mention 14 different methods. The methods used most commonly for 3D metrology of micro/mesoscale parts and features are white-light interferometry, confocal microscopy, fringe projection, and optical microscopy. As would be expected, each has its own relative strengths and limitations. However, certain aspects of optical measurements apply to all methods. Many of these concepts are covered in great detail in the *Handbook of Optical Metrology* [24].

One overall advantage is that optical processes are generally noncontact. This is an advantage at the micro/mesoscale because, as seen in the discussion on touch probes, the small sizes involved often make the parts more fragile or susceptible to damage. However, these being noncontact means, the part is imaged remotely, usually with the optical axis normal to the surface under measurement. This means that optical processes are usually limited to 2.5D.

2.5D means that optical processes can provide information in the third, vertical dimension but with some limitations. The particulars of how the different processes provide vertical measurement are discussed further in the individual subsections that follow. However, the limitations of all the processes are similar. The main limitation deals with the line of sight. If there is no direct line of sight from the optical sensor to the feature to be measured, no measurement can take place. This limitation primarily affects vertical sidewalls and overhangs (e.g., t-slots). Because the vertical sidewalls are usually parallel to the optical axis, there is no direct line of sight from a point on the sidewall to the optical sensor. As such, optical processes may be able to measure the depth of a hole or slot but usually cannot provide information on the taper of a slot or the cylindricity of a hole. A true 3D measurement would provide all this information.

In the sentence "This limitation primarily affects vertical sidewalls and overhangs (e.g., t-slots)." please clarify whether "t-slots" may be changed to "T-slots".

Another issue common to all optical processes is lighting. If the feature or point to be measured cannot be properly illuminated, and the light cannot return to the optical sensor, no measurement can take place. This makes the measurement of high-aspect-ratio holes and slots difficult. Features measured by optical processes usually need to be reflective and should have little slope to reflect adequate light back to the sensor. It is often difficult to optically measure the surfaces of transparent and translucent parts. A more troublesome aspect of lighting is that the quality of the sample illumination often directly affects the measurement. If a certain point is illuminated too much, a portion of the image can appear washed out due to the optical sensor becoming saturated. Alternatively, if a point or feature to be measured is illuminated too dimly, the features in the measured image may be less sharp. Both circumstances affect the apparent resolution of the measurement. Unfortunately, providing quality lighting to a measurement scene is often more of an art than a science.

In the sentence "Features measured by optical processes ..." the meaning of the phrase " should have little slope to reflect adequate light back to the sensor" is not clear. Please consider rewording.

All optical processes discussed in this chapter use intensity measurement in the visible light spectrum as a primary component of the measurement. Intensity deals with the amount of light reaching an optical sensor. For example, edge detection, phase decomposition, and thresholding, all involve the interpretation of intensity in some manner. Thus, uncertainty in intensity measurement will directly affect uncertainty in the optical measurement.

Uncertainty in intensity measurement is rather complicated and comes from several, often correlated, components. The two primary sources of uncertainty in intensity measurement are quantization and noise. Most optical measurements now involve digital electronics that utilize a focal plane array (FPA). The most common FPA device utilized in optical metrology cameras is a charge-coupled device (CCD), and most commercially

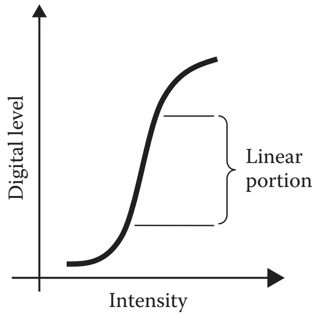

FIGURE 15.5
Intensity response is nonlinear at low and high digital levels, which can lead to large uncertainty.

available optical measurement systems utilize a midlevel camera (as opposed to a high-level camera with superior specifications and characteristics) to keep system prices down. An FPA is actually an array of individual optical sensors termed *pixels*. Each pixel captures light emitted or reflected from the target being observed. Because these devices are digital, the intensity of the light reaching each pixel is broken into digital levels. An eight-bit system divides intensity into 256 digital levels from black (0) to saturation (255), although some cameras use more levels. This is known as *quantization*. However, the division is often nonlinear (Figure 15.5). If linearity is assumed, significant uncertainty will exist at low and high intensities. If nonlinearity is compensated for, uncertainty may be smaller, but it will still exist in the uncertainty of the compensation. The approach with least uncertainty usually involves only working in the linear portion of the intensity plot. However, this limits the range the process can work in and is often impractical.

The two most common noise components are known as *thermal noise* and *shot noise*. Thermal noise in an FPA device is a result of heat from the imaging components causing a change in the free electrons that are mistakenly recorded by the imaging device. Shot noise is a characteristic of all devices that convert a measurement to charge and is defined as uncertainty due to random fluctuations of the charge carriers. Camera data sheets will often attempt to quantify these errors, but unfortunately, it is nearly impossible to measure the two components independently. Many high-end cameras combat thermal noise using a variety of methods to cool the sensor array.

In the sentence "Typically, the size of the FPA chip and the number of pixels in the chip are known, and the pixel size comes from dividing the two." may we modify "comes from dividing the two." as "is obtained by dividing the size of the chip by the number of pixels."?

Other sources of uncertainty in optical measurement may come from the construction of the FPA itself. Typically, the size of the FPA chip and the number of pixels in the chip are known, and the pixel size comes from dividing the two. However, in actuality, there are tiny wires between the pixels that carry the charge into the chip's electronics. Thus, only a certain percentage of the chip (the fill factor) is able to gather light (or measure intensity), and even if that percentage is known, there remains some uncertainty in the size and distribution of the pixels.

Most optical processes are surface profilers that have been adapted to provide dimensional measurement. Because of this, measurements of the vertical dimension typically take advantage of various optical properties and provide measurements with lower uncertainty than measurements of lateral dimensions that almost always involve counting of sensor pixels. While lateral resolution is generally theoretically limited by the wavelength of light used, in most cases, this limit is much smaller than the size of the optical sensor pixel projected onto the feature. As such, uncertainty in lateral dimensional measurements is often a function of the size of the pixel in the FPA, which is not an optical property.

15.3.1 Scanning White-Light Interferometry (SWLI)

Scanning white-light interferometers are readily available, and the process has been widely applied in characterizing micro/mesoscale parts and features [25–29]. Phase-shifting interferometry, common in the field of optics, provides exceptionally low vertical measurement uncertainty (<1 nm possible), but is limited to only surfaces with small slopes. Scanning white-light interferometry (SWLI) can handle very large slopes, even steps, but does so at the expense of higher uncertainty. SWLI extends the vertical range by vertically translating the interferometric objective. Typically, a piezoelectric actuator translates a Mirau interferometric objective (Michelson and Linnik objectives are used less commonly) along the optical axis, and interferograms are collected as the objective is translated (Figure 15.6). Fast Fourier transformation and phase evaluation, searching pixel by pixel for the maximum intensity contrast in the interferogram and comparing this with the *z*-position of that interferogram, allow determination of the surface profile (Figure 15.7) [29]. White light is used because it has a shorter coherence than monochromatic laser light, avoiding fringe ambiguity and allowing better measurement.

Benefits of SWLI are that vertical resolution is independent of optical magnification and that uncertainty in the vertical dimension can be 20 nm or better. However, lateral resolution is associated with the objective's numerical aperture (NA). A smaller NA typically permits a larger field of view and also results in a larger (poorer) resolution. Furthermore, at low magnification, the FPA in the camera collecting the interferograms typically limits the resolution of lateral measurement. Even at these low magnifications, the lateral field of view is typically only a couple of millimeters, much smaller than the larger micro/mesoscale parts. Thus, to completely measure parts larger than the field of view (or if a high-resolution image of smaller features is desired), several neighboring images must be taken individually and stitched together. The machine must move the part between consecutive

Should "larger (poorer) resolution" be changed to "poorer resolution"?

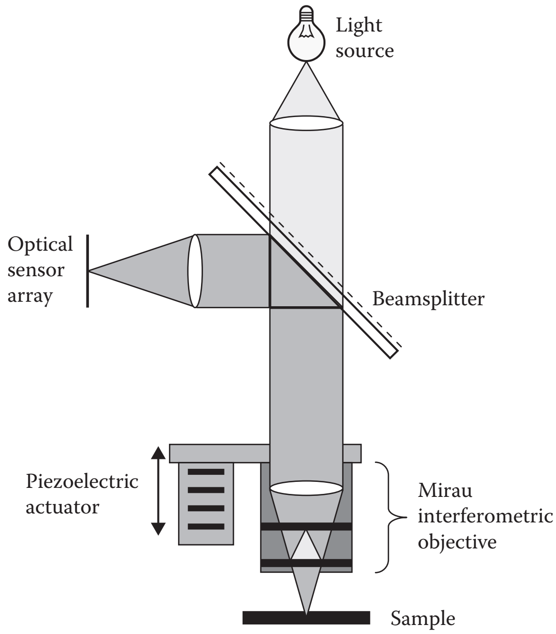

FIGURE 15.6
Schematic of a typical scanning white-light interferometry setup.

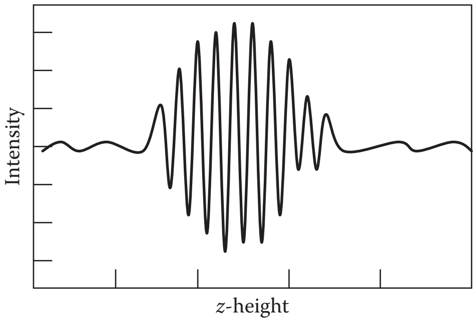

FIGURE 15.7
As the interferometric objective is scanned along the vertical axis, the contrast between fringes is measured and compared to the z-height, allowing the determination of vertical dimensions.

images, introducing the potential for machine tool errors to affect the measurements. This stitching adds another layer of uncertainty to the measurements. Lateral SWLI reduces the severity of this limitation [30].

15.3.2 Confocal Microscopy

In confocal microscopy, the field of view is limited to a very small area. This limitation results in improved lateral resolution over that small area when compared to conventional optical microscopy [31]. The process has found considerable applications in the biological field (live-cell imaging) and has been applied to measurement of micro/mesoscale parts and features [32–34]. The process operates by projecting light through a pinhole onto the workpiece and also collecting light reflected from the workpiece through the pinhole (Figure 15.8). This has the effect of returning light to the detector only when the measurement surface is exactly in focus. As in SWLI, the objective lens is translated along the optical axis. Because light only reaches the detector when the surface is in focus, the height of the surface is found by comparing the peak intensity with the z-height of the objective (Figure 15.9). This is done pixel by pixel to create a topographical map of the surface.

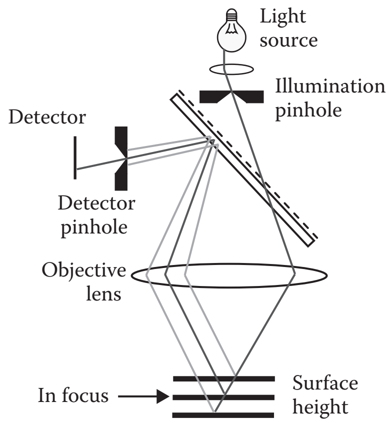

FIGURE 15.8
Schematic of a typical confocal microscope. Note that if the specimen height is not in focus, the light reflected from the surface does not reach the detector.

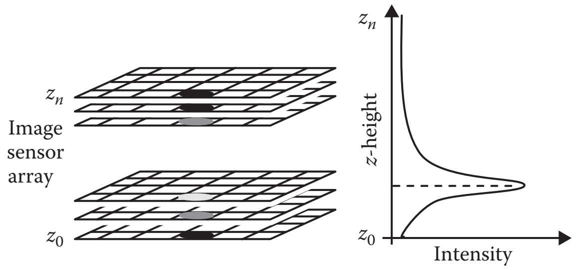

FIGURE 15.9
Schematic demonstrating the determination of the vertical dimension in confocal microscopy. This process is performed for every pixel in the sensor array.

Because the process only views one pinhole worth of a surface at a time, one might think the process would be rather slow. This is not the case, however, because creative solutions allow multiple pinholes to quickly scan over a surface. Older models of confocal microscopes would raster the beam over the surface, similar to the SEM. This process would require several seconds to fill the entire imaging array at only one z-height. However, modern confocal microscopes use a Nipkow disk. A Nipkow disk has a large number of pinholes arranged in a spiral along the surface of a disk (Figure 15.10). Thousands of pinholes ~50 μm in diameter can be illuminated simultaneously, and the disk is spun to distribute the pinholes over the entire field of view. A spinning disk confocal microscope can acquire an entire image in one plane in less than a millisecond. As such, the limiting factor for the process lies more in the vertical scanning and data processing. Acquiring a full 3D image typically takes on the order of several seconds.

Similar to most other optical measurements, vertical and lateral resolutions are different, but lateral resolution of confocal microscopy is better than that of any other optical process. In general, lateral resolution is a function of the pinhole geometry and NA. Pinholes must be arranged such that stray light from an out-of-focus surface does not return to the detector through neighboring pinholes. At 40 x magnification with an NA of 1.2, a lateral resolution of 250 nm is attainable [35]. Unlike in SWLI, uncertainty in the vertical dimension also changes with NA. Uncertainty in the vertical dimension is typically around 50 nm when vertical translation is accomplished by a piezoelectric actuator, but if longer travel is desired to increase the vertical measuring range, a stepper motor can be used for the translation, resulting in poorer uncertainty. The measurement area, when using a Nipkow disk, is similar to that with SWLI, again requiring stitching for larger parts.

15.3.3 Fringe Projection

Fringe projection or structured light processes, although used for inspection of micro/mesoscale features [28, 36], are much less common in the field of micro/mesoscale metrology. Fringe projection is based on photogrammetry and provides 3D measurement through a solution to the stereo correspondence problem [37–39]. Typical photogrammatic solutions to stereo correspondence involve imaging a part with two cameras from two different perspectives and need some type of reference in both images. Fringe projection, however, replaces one camera with a projector that projects a known pattern. This pattern becomes distorted by the shape and contours of the surface on which it is projected (Figure 15.11). The pattern provides the reference and allows corresponding points to be more easily determined automatically.

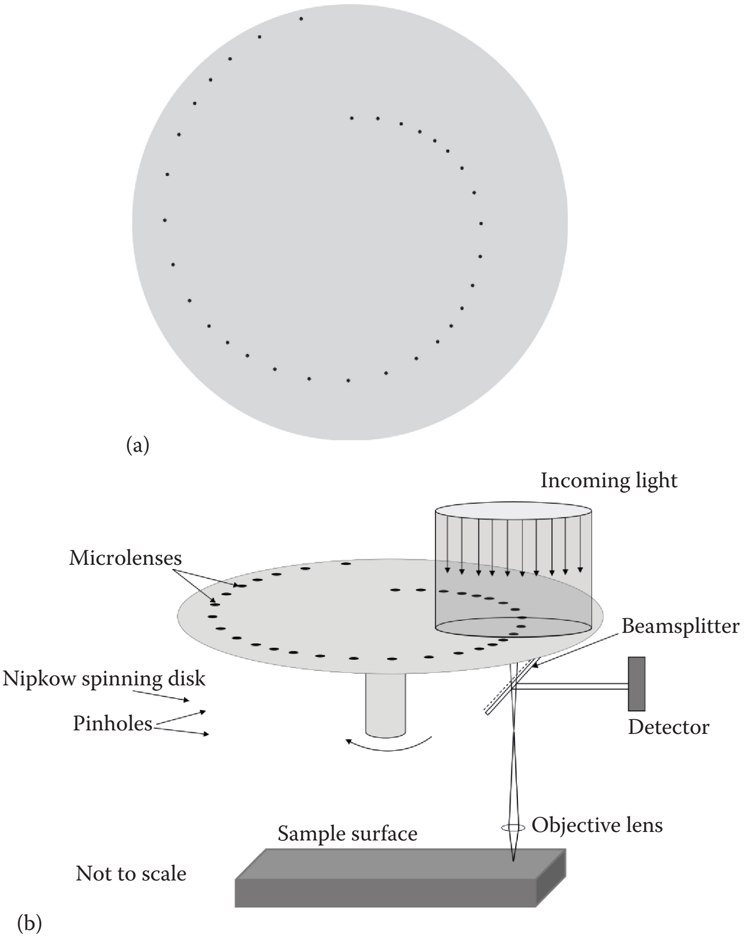

FIGURE 15.10
The Nipkow spinning disk greatly improves the speed of confocal microscopy by allowing multiple pinholes to be scanned over the entire field of view. (a) Spiral design of Nipkow disk; (b) Nipkow disk incorporation into a confocal microscope.

Far fewer commercial systems are available for micro/mesoscale fringe projection than for SWLI or confocal microscopy (though the process is becoming more popular at the traditional scale for noncontact 3D measurement), but literature shows that fringe projection can be equally effective. Windecker et al. [36] reviewed all three processes and measured surfaces of varying roughness, comparing results with output from a stylus measuring device. While SWLI and confocal microscopy proved superior at very low (<500 nm) roughness, fringe projection performed equally well at roughness scales above 1 μm.

Can the sentence "The setup for fringe projection measurement is very flexible …" be modified as "Fringe projection measurement is very flexible …" since the second part of the sentence talks about the setup?

The intrigue with fringe projection stems from the fact that the strengths and limitations of the process are often opposite to those of other optical processes. The setup for fringe projection measurement is very flexible, allowing the setup to be adjusted to accommodate a variety of part shapes. Also, the measurement can be configured to project patterns of various sizes, accommodating a range of part sizes. Digital projection and imaging can easily scale in size to envelop the entire part or feature, that is, the entire part can be measured without stitching and without any movement of the measuring device.

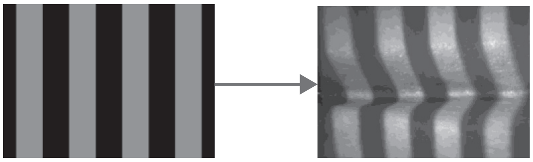

FIGURE 15.11
Demonstration of a typical known fringe pattern and how that pattern is distorted when projected onto a contoured part.

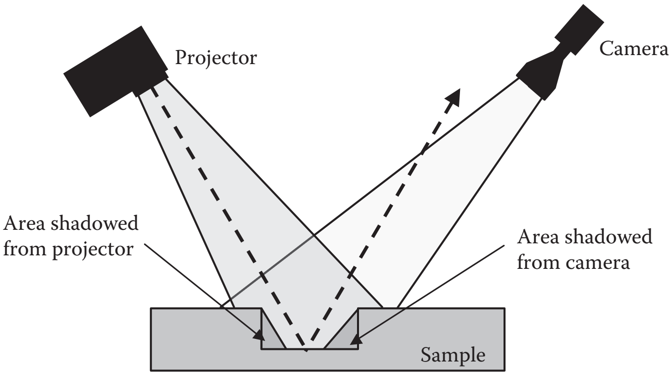

FIGURE 15.12
Shadowing and reflective surfaces are more problematic for fringe projection than other optical measurement processes.

However, shadowing is a larger problem with fringe projection, and highly reflective surfaces cannot be measured (Figure 15.12). Because there are multiple lines of sight in fringe projection, if any of these are obscured from a certain area of the part, that area cannot be measured. Depending on the setup, this may limit the aspect ratio of internal features that can be measured. Also, if the surface reflects all the light from the projector in a direction away from the camera, measurement cannot take place. To avoid these problems, the surface being measured may be coated with a material that scatters light better, and multiple projector angles and camera views may be used.

Determining uncertainty for fringe projection is a complicated matter [40] but is generally larger than SWLI or confocal microscopy. In addition to the sensor uncertainties discussed earlier, the resolution of fringe projection is limited by the size of projector pixels. With the current state of the art, projector pixels are much larger than camera pixels, but the technology is constantly evolving.

May we modify "Determining uncertainty for fringe projection is a complicated matter [40] but is generally larger than SWLI or confocal microscopy. " as "Determining uncertainty for fringe projection is a complicated matter [40] and the uncertainty is generally larger than in SWLI or confocal microscopy."?

15.3.4 Optical Microscopy

Optical microscopy is a very powerful tool for quick, low-uncertainty measurements in two dimensions. Features and patterns can be identified within the field of view, and a well-calibrated vision system can provide low-uncertainty measurements and quick comparison to templates. However, for 3D measurement, optical microscopy is used in a different manner.

To provide 3D measurement, the optical microscope performs more like a CMM except that it has an optical probe instead of a touch probe. As in SEM, it is difficult to obtain information about a part in the vertical dimension. However, in contrast to SEM, an optical microscope has a relatively small depth of focus, especially at higher magnification. Because of this, the feature being inspected is in focus at only one particular height. That position of focus can translate to a measurement in the third dimension with the use of a precise scale on the positioning device. With this type of measurement method, the position of focus is determined automatically (autofocus). The method of determining this position is usually proprietary to the particular system, but a through-focus technique similar to the one described for confocal microscopy is common, although with larger measurement uncertainty. This vertical measurement is combined with the position of the x- and y-axes scales to locate the coordinate of the in-focus feature at the center of the microscope's field of view. If the image system is calibrated, coordinates of features elsewhere in the field of view that are also in focus can be determined by combining the distance from the center of the image with the axes scales' positions.

15.4 Scanning Probe Microscopy

The strength of SPM lies in its superior measurement uncertainty. Under proper conditions, SPM can be used to resolve individual atoms. However, SPM processes are limited in their range to only hundreds of micrometers laterally and tens of micrometers vertically. As such, SPM may be better suited for nanomanufacturing metrology. However, there is important overlap with micro/mesoscale manufacturing that warrants a brief discussion here. A more thorough introduction to SPM and the variety of SPM processes can be found elsewhere [41].

Should "there is important overlap" be modified as " there is significant overlap"?

All SPM processes involve bringing a probe tip into near-field proximity with the part's surface, scanning the probe over the surface, and monitoring a specific interaction between the probe and the surface. Operating in the near-field avoids common limitations on resolution (e.g., Raleigh's criterion) seen in the far-field processes discussed in the previous section. Scanning is accomplished with piezoelectric actuators. The height of the probe is controlled to keep the interaction between the probe and the surface constant. Height adjustments as a function of scanning position provide a topographic map of the measured surface. There are a variety of interactions that can be monitored, leading to as many as 16 different types of SPM.

Can we change "Raleigh's" as "Rayleigh's" in the sentence " Operating in the near-field avoids...". Please confirm.

Scanning tunneling microscopy (STM), scanning force microscopy (SFM), and scanning near-field optical microscopy (SNOM) are the most commonly encountered SPM processes. SFM requires the least amount of sample preparation, can measure electrically nonconductive as well as conductive samples, and has the largest measurement range. Therefore, it is the most pertinent technique to micro/mesoscale metrology. In SFM, the forces between the probe and workpiece are monitored. It is assumed that in the near-field, this interaction is primarily between the atoms at the probe tip and the atoms at the workpiece surface, leading to the common name *atomic force microscopy* (AFM).

AFM probes are typically SiN tips, etched to a near-atomic dimension, mounted at the end of a cantilever (Figure 15.13). When the probe tip is brought into close proximity with the surface, the cantilever deflects by an amount proportional to the atomic force between

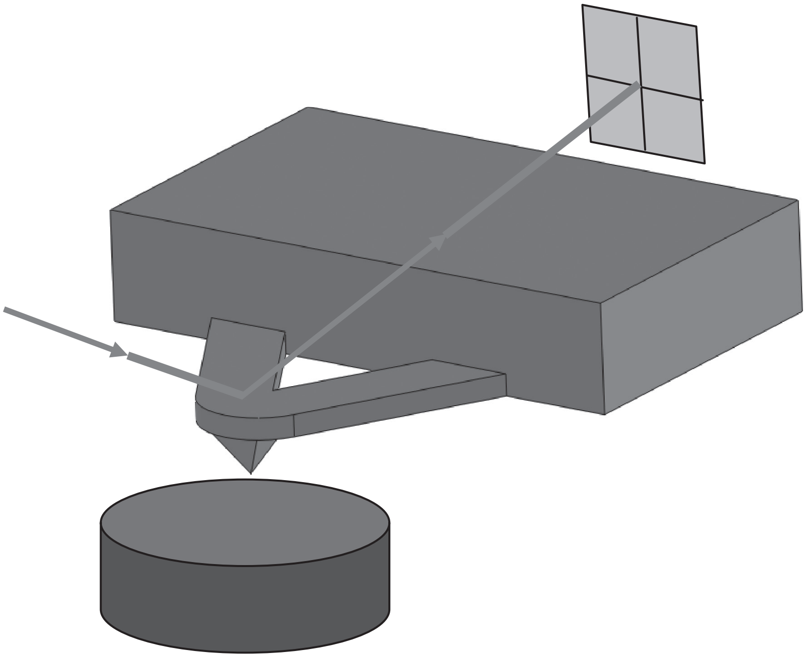

FIGURE 15.13
Beam deflection is a common method of monitoring cantilever deflection in AFM.

the probe and the surface. The amount of deflection is commonly monitored by beam deflection (Figure 15.13). A laser beam is deflected from a source, off the top of the cantilever, and to a position-sensitive photodiode. As the cantilever deflection changes, the position of the beam on the photodiode also changes. Less commonly, cantilever deflection can be monitored through embedded piezoresistive or piezoelectric material, interferometry, capacitance, or tunneling current.

There are also several different types of AFM, classified into dynamic and static methods. The most common static method is referred to as *contact AFM*. With this variant, the probe tip is brought to within the region where the forces between the tip and the surface are repulsive. As the probe is moved, the probe height is controlled to result in the same amount of cantilever deflection. Noncontact AFM is a dynamic process. The probe tip is oscillated near its eigenfrequency, and the probe height is controlled to keep this frequency constant. Noncontact AFM is the only SFM process to achieve atomic resolution. Between these two variants is another dynamic process termed *tapping AFM*. The probe tip is vibrated by approximately 20–100 nm such that the probe tip moves in and out of the repulsive force regime. The probe height is controlled to provide a constant amplitude of vibration. Tapping AFM has the advantage of being limited in resolution only by tip geometry, similar to contact AFM, but with significantly lower lateral forces than encountered in contact AFM.

The resolution of an AFM, when operated under proper environmental conditions, is primarily limited by tip geometry. The tip can be thought of as a cone or a pyramid. The height and angle of the pyramid as well as the sharpness of the tip are the important limiting factors (Figure 15.14). Because of this, uncertainty in the calibration of AFM probe tips is important to low-uncertainty measurement.

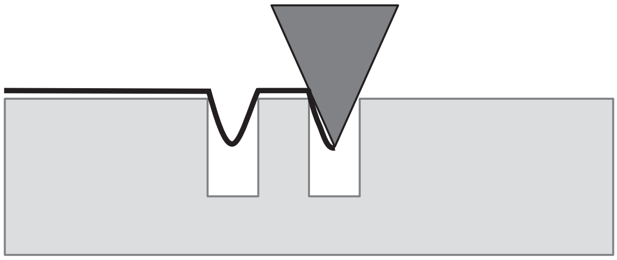

FIGURE 15.14
Tip geometry is a main factor in contact AFM and tapping AFM resolution.

15.5 Hybrid Processes

It is easy to imagine that in the absence of the development of a new measurement process, all future commercial micro/mesoscale metrology devices will be hybrid systems. As seen in the previous sections, every measurement process has trade-offs. Micro-CMMs trade speed for range and low uncertainty. Other processes trade measurement area (lateral range) for lateral uncertainty or resolution. No one process can meet the high demands of micro/mesoscale part and feature manufacturing. Hybrid processes draw from the strengths of multiple processes to overcome the limitations of the involved processes and meet the measurement demands of the part.

Presently, almost all CMMs marketed toward micro/mesoscale parts offer a multiprobe solution. These machine builders realize that manufacturers producing micro/mesoscale parts often produce a small volume of a wide variety of parts. These manufacturers require a measurement device capable of handling this variety. Parts that require quick measurement or are too fragile for contact measurement can be measured with an optical probe or a laser probe. Parts that require real 3D measurement or do not reflect light adequately can be measured by the machine's touch probe.

Alternatively, many micro/mesoscale parts have the high demand of a large number of measured points with extremely low uncertainty measurement over a long range. The concepts of precision engineering will be necessary to conduct these types of measurement [42]. There is considerable research toward utilizing the range of CMMs and combining it with the low-uncertainty measurements capable of quickly measuring a large number of points. AFM probes have been mounted on CMMs [43, 44]. The capabilities of SWLI are being extended to utilize them more like CMMs [45]. When extending the range of these processes, fiducials can be used to reduce measurement uncertainty [46].

15.6 On-Machine Metrology

In situ or on-machine metrology has been called the *holy grail* of discrete part manufacturing and will have a large impact on high-value manufactured products. Typical micro/mesoscale parts are inherently more valuable than typical traditional-scale parts.

On-machine measurement can reduce the number of scrapped parts by immediately identifying and correcting for errors in the manufacturing process.

Many manufacturers think of metrology as a "non-value-added" process because postprocess metrology requires taking the part away from the production line. Despite the flaws in this reasoning, on-machine measurement appeases these manufacturers because the measurement process takes place within the production line, eliminating the time lost in moving the part to a separate measurement machine, possibly in a separate, dedicated room or facility. In fact, on-machine measurement could make a separate metrology facility unnecessary, allowing a manufacturer to use space originally allotted to metrology for further production.

An additional impact is the fact that on-machine metrology does not require reregistration of the workpiece. When the workpiece is first fixtured to the machine tool, key datum surfaces are established to register the part within the machine's coordinate system. Features are then machined relative to these surfaces. With postprocess measurement, these datum surfaces would need to be reestablished on the metrology device. With on-machine measurement, because the part is not removed from the machine's fixture, the time required to reregister the part is eliminated, but more importantly, the errors in the workpiece are better connected to the errors in the machine tool.

Better connection between machine tool and part errors has several impacts. Of primary importance is that after part errors have been detected, the user or the controller can correct these errors on the current part or compensate for the errors on subsequent parts. This leads to fewer scrapped parts. Also, part errors can help to more quickly diagnose a machine or a tool trending out of tolerance. A change in surface roughness between two parts might indicate that a tool change is necessary.

While these advantages will impact all scales of manufacturing, micro/mesoscale manufacturing further benefits from on-machine inspection. The virtue of not needing to reestablish datum surfaces was previously mentioned, but micro/mesoscale parts further benefit because components are much smaller and absolute tolerances are smaller, making part registration more difficult and time consuming. Also, fixturing of micro/mesoscale parts is significantly more difficult than traditional-scale parts, often requiring unique fixturing solutions for individual parts. With postprocess measurement techniques, a fixturing solution for measurement would be necessary in addition to the fixturing solution for machining, adding significant time and cost. With on-machine measurement, only one fixturing solution suffices.

An additional benefit to micro/mesoscale parts is the reduction in handling that results from on-machine measurement. Micro/mesoscale parts are small and often fragile, presenting unique handling issues not encountered on the traditional scale. Pick-and-place robots with gripping end effectors aid in automation at the traditional scale and could avoid problems created by human handling at the micro/mesoscale. However, issues with adhesion discussed in the touch probe section are more troublesome in handling. If the part does not move from its fixture, as is the case with on-machine measurement, the location of the features is already known, allowing immediate start of the measurement cycle. Of course, any time a part is handled, there is the chance of damaging the part or surface. The lack of handling between machining and measurement greatly reduces the likelihood that the part is harmed in this phase of production.

A major challenge of on-machine metrology is the decoupling of machine tool errors from measurement uncertainty. No machine is perfect, so when the machine moves to produce the part, error motions will result in part imperfections. If the same machine again moves to perform the measurements, the same error motions will likely repeat, obscuring the part imperfections from the measurement. This is a significant obstacle, and if not properly addressed, will defeat any advantage on-machine measurement can offer.

Another consideration should be the harsh environment in which the metrology device would reside. Postprocess measuring devices typically reside and operate in a controlled environment ideal for measurement. On-machine devices would obviously reside on a machine tool and must be able to properly operate whether the machine tool is in a conditioned environment or on the shop floor. The metrology device would need to be able to survive the harsh machining environment that could see flying chips and cutting fluids. Proper measurement requires removal of any debris from the machining process, deburring, and thorough cleaning of the part surfaces. However, this cleaning must be accomplished without removing the part from the fixture—no trivial task. In addition, thermal expansion could more significantly affect on-machine measurements than postprocess measurements. The machine likely just moved a significant amount with the spindle on, producing a considerable amount of heat. This heat could cause expansion of important machine components or even the part itself.

The meaning of the sentence "The metrology device would need to be able to survive ..." is not clear. Please rephrase for better clarity.

Again, the unique attributes of micro/mesoscale machining present further important considerations. The recent high demand for smaller parts has led to the development of new micro/mesoscale machine tools, significantly smaller than their traditional-scale cousins and often with different designs. An on-machine measurement device would need to operate within the confined work volume of any micro/mesoscale machine tool, often only 25 mm × 25 mm × 25 mm. This does not provide much space for large optics, supporting electronics, or stray cables. Also, while an on-machine measurement solution that succeeds on only one specific machine design would be progress, a more robust solution that fits many machine designs is more desirable.

15.7 Summary

This chapter presented an overview of processes typically used for 3D metrology at the micro/mesoscale. None of the processes discussed was specifically developed to operate with micro/mesoscale manufactured parts (see Table 15.1 for typical uses). Because

TABLE 15.1

Since Many Micro/Mesoscale Metrology Processes Are Adaptations of Existing Methods, They Are also Used in a Variety of Other Fields

Process	Common Fields of Application
CMM	Traditional-scale geometric part metrology microhole characterization
SPM	Biological applications, semiconductor wafer measurement, microstructural analysis, nanomanufacturing
WLI	MEMS devices, surface texture metrology, semiconductors (step heights, critical dimensions, topographical features)
CM	Biotech, molecular biology, living cell observation, printer head measurement, high aspect ratio samples, MEMS
FP	Molds and plastic molded parts, reverse engineering

CMM, coordinate measuring machines; SPM, scanning probe microscopy; WLI, white-light interferometry; CM, confocal microscopy; and FP, fringe projection.

Please confirm if the abbreviation "MEMS" needs to be defined. If"yes" please define the same.

TABLE 15.2

Summary of the Capabilities of the Discussed Micro/Mesoscale Metrology Processes

Process	Contact (C) or Non-contact (N)	Vertical Uncertainty (nm)	Lateral Uncertainty (nm)	Measurement Size	Commercial Systems	Strengths	Weaknesses
CMM	C	25	25	Probes down to 100 mm	Few in microscale	Low uncertainty, very well characterized	Probe size; slow; environmental control
SPM	N	1 or less	1 or less	200 mm × 200 mm; 15-mm *z*-range	Many	Superior uncertainty, variety of measurements	Small scan size; limited *z*-range; environment control
WLI	N	20	300[a] at high mag.	2 mm × 2 mm down to[a] 70 mm × 70 mm	Many	Vertical resolution	Diffraction limited; working distance
CM	N	50	1000[a] 150	Up to 2 mm × 2 mm[a], 550 mm × 550 mm, 70 mm × 70 mm	Many	Lateral resolution; long *z*-scan available	Diffraction limited; working distance
FP	N	<100	5000	100 mm and up	Few	Large field of view; fast	Large uncertainty; less developed

All values are approximate and are based on specification sheets of various commercially available systems.

[a] Measurement size and uncertainty vary with numeric aperture on optical systems. Cited values are for commonly available optics.

In Table 15.2, please clarify whether the words "working distance" (two instances) should be followed by any other text describing the working distance. If yes, please provide the missing text.

of this, trade-offs exist with each of the processes. Table 15.2 summarizes the capabilities and availability of the discussed processes. Because of the inherent high value and high demands of micro/mesoscale parts, hybrid processes and on-machine metrology are likely the future of micro/mesoscale manufacturing.

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