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Dimensional measurement of 3D microstructure based on white light interferometer

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Abstract. Dimensional metrology for micro/nano structure is crucial for addressing quality issues and understanding the performance of micro-fabricated products and micro-fabrication processes. Most of the established methods are based on optical microscopy for planar dimensions and stylus profilometry for out-of-plane dimensions. Contact profilers suffer from slow speed of measurement for three-dimensional profiles and are not suitable for delicate surfaces and parts. Advanced systems using white light interferometer are equipped with CCD cameras and interfaced with a microscope to conduct an array of measurements ranging from two-dimensional to three-dimensional profiles and surface roughness analysis. This paper presents a methodology based on white light interferometer for the dimensional measurement of 3D micro-structures, demonstrated on micro-gears and moulds produced by UV lithography and vacuum casting, respectively. Physical artifacts, such as gauge blocks, are also utilized to verify and validate the measurements on the microcomponents.

Keywords: methodology; microcomponents; metrology; surface roughness; white light interferometer

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1. Introduction

Many of the Micro-Electro-Mechanical-System (MEMS) processes developed from lithography-based microfabrication and micromachining techniques are commonly derived from the microelectronics industry and offer the potential of great cost reduction in batch fabrication processes for high-volume manufacturing [1].

To minimize errors, a metrology system for MEMS must have sub-micron precision, sub-millisecond sensing, and reliable and robust performance in harsh environments, and miniaturized hardware that can be easily integrated into existing systems [2]. It is crucial for addressing quality issues of micromanufactured products and processes. The quality issues may be divided into two equally important phases: R&D and production. From an R&D perspective, metrology is essential for understanding the performance of newly developed products and processes. From a production standpoint, metrology is necessary to ensure that the products are fabricated correctly. In due course, the assurance of producing products that are in specification requires that the production process be controlled.

In micromanufacturing dimensional metrology, it is interesting to note that many of the inspections are still accomplished by optical microscopes or scanning electron microscopes (SEM), although SEM does not reflect accurate 3D dimensions and style contact profiler is not suitable for delicate surfaces that may be damaged by the stylus. Most published results and measurements are based on SEM, with few from the white light interferometry (WLI). In view of these, the main metrology equipment used in this paper as benchmark and comparison would be WLI systems, which are the Veeco WYKO® NT1100 [3] and the Zygo NewView 5000™ [4].

Optical profilers, also known as WLI, appears to be the leading metrology equipment for small 3D objects as WLI can image for 3D metrology based on interferometric measurements. Other qualities include high-speed data acquisition, wide measurement area, large vertical range and sub-nanometer vertical resolution as well as the ability to measure 3D profiles in one measurement where in usual engineering surfaces, the measurement field should cover an area of several square millimeters [5]. This unique set of strengths supports a variety of metrology applications in R&D, product and process development, manufacturing, and quality control. Various 3D metrology techniques can be summarized in two categories: contact and non-contact.

1.1. Contact Method

Conventional contact measurement in 3D surface profiling and roughness measurements has been a reliable method for hard sample surfaces and the contact methods are insensitive to optical properties of the surface such as transparency.

The 4 common contact types of equipment are: Contact Stylus Profiler, Coordinate Measurement Machine (CMM), and Scanning Probe Microscopes (SPM).

1.1.1. Contact Stylus Profiler. It is widely used to monitor chemical mechanical planarization (CMP) performance in electronics fabrication [6] and are typically used to measure step heights, long-range planarity, and long-range variations in local surface roughness in a single scan usually. Inevitably, the limits of the amplitude, which can be measured, and the limits on spatial wavelengths are restricted by the physical dimension of the stylus tip and its angle [7]. In addition, stylus profilers can measure step heights on vertical and near-vertical steps taller than those possible with the AFM, such as a silicon micro-probe with a sharp tip used to measure the inner profile of high aspect-ratio microstructures [8].

1.1.2 Coordinate Measuring Machine (CMM). CMMs have revolutionized the dimensional metrology of virtually all types of manufactured components not only for their accuracy, convenience and simplicity of operation but also because of the wide range of industries covering a broad array of applications [9]. With several measuring sensors integrated with the equipment such as optical sensor, it is capable to perform the same function as the microscope-based inspection systems, contact tactile
measurement head similar to that of contact stylus probe, and a vision system that is used to aid in the positioning of the tactile probe [5]. Takaya et al. [10]-[11] developed a laser trapping probe for nano-CMM. It can achieve a possible resolution of 10 nm and has a measuring force of 0.01mN, which makes it possible to achieve nanometer sensitivity, comparable to the AFM.

1.1.3 Scanning Probe Microscopes (SPM). The big difference between SPM and the conventional stylus is that they rely for their signal on quantum-mechanical effects, such as tunneling current for STM. AFM and STM can measure deflections that are much less than 1 angstrom (Å). Hence, they are the most common method used for surface roughness measurement in the nano scale.

The major advantage of these new-generation microscopes is their ability to measure more than one feature. In STM, by varying the voltage between the specimen and the probe tip, the instrument can be used as a topographer and spectroscope widely used in the measurement and detection of growth in biological specimen, the machining of substrates, and the microfabrication.

By utilizing this basic technique in STM to detect deflection in AFM cantilevers, other varied techniques [12] evolved such as magnetic force microscopy (MFM) where the probe is magnetized, electrostatic microscopy (EFM) where the probe has an electrostatic charge, scanning thermal microscopy (SThM) where the probe acts as a thermocouple and near-field scanning optical microscopy (NSOM) where the probe is in fact a sub-micrometer aperture [13].

1.2. Non-contact method

Non-contact measurement is of significant interest because it avoids deformation of the products and mechanical errors in the contact measurement. Hence, they are suitable for very delicate machined surfaces. The basic principle of an active non-contact range finding system is to project a radio-wave, ultrasonic, or optical source onto an object and process the reflected signal to determine its range.

The 4 common types of non-contact equipment are: Confocal Scanning Optical Microscope (CSOM), White Light Interferometry (WLI), Scanning Electron Microscope (SEM) and Tunneling Electron Microscope (TEM).

1.2.1. Confocal. Scanning Optical Microscope (CSOM). CSOM is primarily used to measure the topography of biological tissues and 2-D profiles [14] but has been introduced for 3-D measurement through reconstruction of a volume of the specimen and assembling a series of thin slices taken along the vertical axis [15]. Udupa et al. [16]-[17] applied CSOM to micro and macro surface irregularities and concluded that it was a useful tool for this purpose.

1.2.2. White Light Interferometry (WLI). Interferometry is popular for surface profiling. Generally, this mode utilizes the coherent property of the light, the interference between the light and that scattered from the test surface and from a reference surface such as a glass flat surface to produce fringes. The fringe contours can then be examined through the contour pattern when viewed, to derive a very clear picture of the general surface geometry. If the fringes are sharpened up by means of multiple-beam interferometry, the surface roughness can be measured. Furthermore, WLI does not involve phase shifting or complex algorithms, and is theoretically unlimited in the vertical scan length, which is only constrained by how far the reference mirror can move.

The drawbacks of an interferometer are that it cannot read discontinuities of the object geometry as in the case of sharp edges, and only works in relative coordinate space. These sharp edges can produce misleading diffraction spikes which can be mistaken for real peaks and thus can be a major problem in calibration.

1.2.3. Scanning Electron Microscope (SEM). SEM is the most common equipment being used to illustrate scale of the microstructures but the drawbacks of SEM are the distortion produced by sharp edges, curvatures and slopes in the object which are qualitative in nature, making calibration a problem. Inevitably SEM is widely utilized in imaging rather than for metrology.
1.2.4. Tunneling Electron Microscope (TEM). TEM is generally well suited to thin samples where higher order of electron energy than SEM is used. Moreover, a high energy source means a smaller de Broglie wavelength and this implies a smaller feature or simply higher resolution up to atomic (angstrom)-level than SEM. However, TEM is not as important in surface metrology because most engineering surfaces are opaque and since the energy beam is traveling through the sample, the sample bulk and not the surface is being imaged.

| Equipment               | Mode      | Resolution Lateral | Resolution Vertical | Resolution Vertical |
|-------------------------|-----------|--------------------|---------------------|---------------------|
| Stylus                  | Contact   | 0.1 μm             | 0.3 nm              | 50 μm               |
| CMM                     | Contact   | 10 μm              | 10 nm               | 10 mm               |
| AFM                     | Contact   | 0.5 nm             | 0.05 nm             | 6 μm                |
| STM                     | Contact   | 2.5 nm             | 0.2 nm              | 100 nm              |
| Confocal Microscope     | Non contact | 1 μm            | 0.1 μm              | 50 mm               |
| WLI                     | Non contact | 0.45 μm          | 0.1 nm              | 5 mm                |
| SEM                     | Non contact | 10 nm           | 2 nm                | 2 μm                |
| TEM                     | Non contact | 2 nm to 1 μm     | 2 μm                | 100 nm              |

2. White Light Interferometry (WLI)

![Image of white light interferometry](image)

**Figure 1.** Basic configuration of white light scanning interferometry.

Typically, in an interferometer a beam of white light or monochromatic light source splits into two separate beams and is then recombined. The resulting interference occurrence is subsequently recorded in the form of an interferogram [18], which is a discrete fringe pattern, and is processed by
the computer for data measurement and analysis using various phase mapping techniques, such as phase-shifting interferometry (PSI) and vertical scanning interferometry (VSI). Data analysis of the sample, such as average roughness, peak-to-valley height, 2D and 3D false-color height maps, histograms, bearing ratio, curvature, and volume analysis, etc are eventually possible depending on the software applied. Figure 1 shows a typical set up of the scanning interferometry of WLI.

2.1. Principle of Operation
Using the Veeco WYKO NT 1100 as an example, the working principle of a WLI shown in figure 2 can be illustrated in the following steps:

- White light from the illuminator generated by a halogen lamp travels through the aperture stop and field stop. The aperture stop controls the focusing of the light while the field stop controls the field-of-view (FOV) on the charged-coupled-device (CCD) camera.
- Bypassing the field and aperture stop, the light is reflected down to the interferometer (interfaced with a translator, reference mirror, and a microscope objective) by a beam splitter.
- Once the light reaches the objective, another beam splitter separates the light into two beams. One beam, the reference beam, reflects from a super smooth reference mirror inside the objective, while the other (the test beam) reflects from the surface of the sample and back to the objective.
- If the surface of the sample is in focus, as shown in figure 3, the two light beams will recombine to create bright and dark bands called “fringes” that make up the interferogram. Fringes, like lines on a topographic map, represent the topography of the object and can be used to gauge the surface roughness of the sample object. The number of fringes and their spacing depend on the relative tilt between the sample and the reference mirror.
- Subsequently, during the scanning, the reference surface is translated relative to the test sample by the translator such that every point on the surface passes through the focus. Throughout the scan, a series of intensity of data frames, which are shown as interferograms, is recorded by the CCD detector and the data frame is forwarded to the computer for processing.
- Finally, these frames are analyzed using various interferometric phase mapping programs, such PSI for surfaces below 160nm, and VSI for surfaces above 160nm [19] to determine the height of each point on the surface. Using these data, it is now possible to analyze the sample in details using appropriate software.
3. Metrology Samples and Equipments

Prior to any part geometry validation, it is crucial that the readings and measurements obtained from the measuring instrument are accurate and precise. Hence it is necessary to conduct a preliminary analysis using metrology sample of calibrated dimensions to check the equipment accuracy and precision.

To compare the limitation and/or capability of the equipment, a master micro-gear created by UV lithography, and a cast micro-gear and micro moulds made by vacuum casting are measured and analyzed.

3.1. Metrology Samples and Gage Blocks

Several 1mm diameter micro-gear and micro-moulds samples (figure 4), together with the other test components of known dimensions, which are the photo mask (figure 5) and gauge blocks, are utilized to assess the capabilities and limitations of the metrology equipment based on benchmarking and performance measures with respect to various metrology criteria and principles.

Gauge blocks are defined internationally by ISO specification [20] with flat and parallel opposing surfaces, and are high-precision calibrated artifacts of known dimensions used as calibration gages in equipment performance validation and dimensional calibration. A Grade 00 gauge block certified by ISO Standard 3650 is used for step height analysis, while a photo mask (figure 5) is used for lateral comparison of geometric dimensions.

3.2. Metrology Aspects and Features of the Samples

A set of measurements is defined to describe the micro-gear or micro-gear cavity shown in figure 6 and figure 7.
For micro-gears made of SU-8 (by UV lithography), wax and polyurethane (by casting), the gear diameter, hub diameter, hub width, gear height and surface roughness of the gear top surface are selected for this purpose. For micro-gear cavities in the silicone rubber moulds, similar features are measured.

The difference between the gear pattern and cavity metrology features in the selected surfaces lies in the fact that the top surface of the gear is copied onto the mould as the bottom surface of the cavity.

In addition, the photo mask shares the same measurement features, but the surface roughness and thickness are not considered.

4. Results and Discussion

4.1. Gauge Block Analysis

The measurements selected for gage block 5, 10, 20, 30, and 40 μm, each repeated 15 times. Table 2 below shows the summarized tabulated results.

| Metrology Equipment       | Gage Block Thickness |
|---------------------------|----------------------|
|                           | \( \bar{X} \pm 2\sigma \) |
|                           | 5 μm | 10 μm | 20 μm | 30 μm | 40 μm |
| Veeco optical profiler    |      |       |       |       |       |
| (5X Michelson Objective)  | 5.007 μm | 10.214 μm | 20.002 μm | 30.178 μm | 40.253 μm |
|                           | ± 41.8 nm | ± 43.2 nm | ± 55.8 nm | ± 15.3 nm | ± 16.2 nm |
| Zygo optical profiler     |      |       |       |       |       |
| (5X Michelson Objective)  | 5.529 μm | 10.260 μm | 20.254 μm | 30.247 μm | 40.214 μm |
|                           | ± 31.6 nm | ± 34.2 nm | ± 44.4 nm | ± 42.8 nm | ± 22.6 nm |
From table 2, it can be observed that both white light optical profiler and contact stylus have a standard deviation of less than 70nm or 0.07 μm, as compared to the Keyence digital microscope and CMM laser probe of standard deviation greater than 1400nm up to 3000nm at 95% coverage.

4.2. Micro-gear Samples Analysis

The gear diameter (outer and inner), hub diameter, hub width, gear height and surface roughness of the gear top surface are measured by the equipment and compared accordingly. Figure 8 shows a sample of the results taken from WLI (Veeco and Zygo optical profiler), CMM, SEM, and optical microscope respectively.
Figure 8. Outer diameter measured by (a) Veeco and (b) Zygo optical profiler (c) CMM (d) SEM (e) Keyence digital microscope (f) Leica digital microscope.

The outer diameter measured by both WLI are generated by the software (figure 8(a), 8(b), 8(e) and 8f) while simple subtraction is need for CMM (figure 8(c)). The results clearly show that SEM could not give accurate dimension reading.

The outer diameter for both the microgears and micro-cavities is defined as the average tooth-to-tooth distance of two oppositely-facing gear teeth. As shown in figure 8(e) and 8(f), there are eight possible orientations by which the tooth-to-tooth distance can be measured. Measurements were taken from these eight orientations to account for any non-uniformity or roundness in the gear. The measurement at each orientation was repeated to reduce the operator’s error and the error imposed by the equipment tolerance.

4.3. Photo mask Analysis

By using a photo mask for UV photolithography, it is possible to validate the accuracy of the lateral pixel density assigned by the metrology equipment and also to verify the photo mask gear features. Only selected equipment is used for analysis due to limitation to hold the photo mask. Results of the analysis are illustrated in table 3 below.

Table 3. Results for Photo mask analysis.

| Metrology Equipment                    | Photo mask | Diameter |
|---------------------------------------|------------|----------|
|                                       |            | Hub Width | Outer | Inner |
|                                       |            | 100 μm    | 1000 μm | 360 μm |
| Veeco Optical Profiler                |            |           |        |       |
| - 5X Michelson for diameter analysis  | 99.80      | ± 0.566 μm| 997.81 | ± 1.96 μm| 359.44 | ± 1.93 μm|
| - 50X Mirau for hub width analysis    |            |           |        |       |
| Zygo Optical Profiler                 | 100.57     | ± 1.69 μm | 998.00 | ± 3.10 μm| 358.94 | ± 3.22 μm|
| - 5X Michelson for diameter analysis  |            |           |        |       |
| - 50X Mirau for hub width analysis    |            |           |        |       |
| Leica Digital Microscope             | 99.76      | ± 0.892 μm| 999.19 | ± 1.56 μm| 359.60 | ± 1.22 μm|
| - 5X for outer diameter analysis      |            |           |        |       |
| - 20X for inner diameter and hub width analysis | ± 0.752 μm | ± 1.40 μm | ± 11.85 μm |
| Keyence Digital Microscope           |            |           |        |       |
| - 175X for outer diameter analysis    | 100.67     | ± 0.752 μm| 1054.99| ± 1.40 μm| 371.67 | ± 11.85 μm|
| - 450X for inner diameter and hub width analysis |            |           |        |       |

4.4. Surface Roughness Analysis

Surface roughness is typically measured by AFM and contact profiler. Here, we compared the surface roughness of a PU microgear measured by 3 different types of equipments. Table 4 summaries the results.
Table 4. Surface roughness of PU microgear.

| Metrology Equipment                  | Average Surface Roughness, Ra (nm) of PU micro-gear |
|--------------------------------------|-----------------------------------------------------|
| Optical Profiler                     | 20.53 ± 2.52                                        |
| (Veeco WKYO NT1100)                  |                                                     |
| Optical Profiler                     | 26.85 ± 1.25                                        |
| (Zygo NewView 5000)                  |                                                     |
| CMM (Mahr OMS-400 CMM)               | N.A                                                 |
| SEM (Jeol JSM-5500 SEM)              | N.A                                                 |
| Digital Microscope                   | N.A                                                 |
| (Keyence VHX-100)                    |                                                     |
| Digital Microscope                   | N.A                                                 |
| (Leica DC 300)                       |                                                     |
| Contact Profiler                     | 11.64 ± 2.29                                        |
| (Talysurf -120 stylus Profiler)      |                                                     |
| AFM (SPA-500 AFM)                    | 7.85 ± 0.46                                         |

From the average roughness $R_a$, Zygo optical profiler (26.85nm), Veeco optical profiler (20.53nm), Talysurf profiler (11.64nm), and AFM (7.85nm), this serves to affirm the deduction regarding stylus, which reduces the signal-to-noise ratio, while the optics appears to increase the noise described by Whitehouse et al. [21].

Contact profiler is not suitable for delicate surface and figure 9 illustrates the surface damage. Hence, the micro-indenting force lower reading is likely to cause the reading to be much lower.

Scratched surface after contact profiling

Figure 9. PU microgear surface before and after measurement by contact profiler.

WLI can generate 3D view of the micro-gear with several dimensional details, such as height, surface roughness, outer diameter etc in a single scan. In addition, it will not damage the delicate surface compared to contact profiler. (figure 9)

5. Conclusion

Until now, most inspection that is currently done is accomplished using optical microscopes, SEM and TEM. Metrology with these microscopes is executed using images from the microscope in conjunction with calibrated markings which must be specially calibrated to make use of the scale markings [5]. For both optical and electron microscopes, the scale markings are generally intended to provide a “feel” for the size of the image, rather than a precise tool for metrology.

Although AFM system has the capability to resolve geometric features at the atomic level, such resolution is too fine for most micro-component applications.
As for the conventional tactile stylus profiler, this equipment was mainly used for roughness measurements. The disadvantages are the slow data acquisition by line scan, and for many surface types, the resolution of the equipment being significantly limited by the size of the stylus probes, and the possible damage and scratching of soft, adhesive samples such as the wax cast gear.

Analysis and tests on the equipment show that both the optical profilers, namely Veeco WYKO® NT1100 [3] and the Zygo NewView 5000™ [4], demonstrate excellent repeatability and accuracy, and the former has been selected as benchmark criterion in subsequent qualitative dimensional analysis of micro-manufactured structures.

Four types of micro-manufactured components, which require geometric analysis, have been analyzed. They are SU8 master gear pattern, silicone rubber mould cavity, PU-polyurethane cast microgears. Through dimensional analysis of these micro-components, it also leads to further deduction on some of the limitation and capabilities of the equipment for micro-metrology.

In general, stylus instruments reduce the signal-to-noise ratio while optical interferometer reduces the ratio, as described by Whitehouse et al. [21].

Furthermore, stylus equipment could damage and cause inaccuracy due to the inherent micro-indenter asserting contact force between the probe tip and sample. Secondly, the scale marking provided on SEM is intended to provide a gauge for the size of the image rather than as a precise measurement for metrology. Thirdly, most microscopes serve as inspection tools only, less used with calibrated optics. The measurement range of most microscopes is limited, and/or high resolution is usually only obtainable within a small measurement range due to the limitation of the pixel size or length.

Hence, we believe that WLI is deemed to be much more suitable for measuring microstructures compared to existing methods in this case as it is capable of measuring the dimensions as well as the surface roughness without any damage to its surface in a single scan.

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