Dimensional Metrology in Micro Manufacturing

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Abstract

The need for dimensional metrology at micro and nano scale is evident both in terms of quality assurance of components and products and in terms of process control. As critical dimensions are scaled down and geometrical complexity of objects is increased, the available measurement technologies appear not sufficient. New solutions for measuring principles and instrumentation, tolerancing rules and procedures as well as traceability and calibration are necessary if micro manufacturing is to develop into industrial manufacturing solutions. The current paper describes issues and challenges in dimensional metrology at micro scale by reviewing typical measurement tasks and the measuring capability of available instrumentation. Traceability and calibration issues are discussed subsequently. Finally needs and gaps are identified based on these observations.

Keywords: dimensional and geometrical metrology, micro manufacturing, tolerancing

1. Introduction

Miniaturisation has been one of the driving forces of technology during the last 20 years. As predicted by Taniguchi in 1983 by now the technologies have moved into the nano-processing era and even for precision machining processes sub-μm precision is achievable [1]. This development has been made very clear in the semiconductor industry during the last 30 years, where the number of components on a chip has been doubled each 18 months approximately. This phenomenon is usually referred to as Moore’s law. Today the semiconductor industry is moving below 90 nm in pitch and need for proper process and quality control is evident [2-4].

The emergence of micro-electro-mechanical systems (MEMS) has mainly been based on the advances of the semiconductor technologies allowing mechanical based systems manufactured using production systems developed for electronics. The number of new products based on these technologies is increasing. The development has furthermore been pushed into non-semiconductor materials like polymers and metals, and this has resulted in more traditional manufacturing technologies being applied to micro manufacturing. Integration of micro scaled features and components on meso or macro scale devices as well as nano scale integration on micro scaled devices push all technologies to the limits of their capability, and at the same time the integration over several orders of magnitude on the length scale poses enormous problems for quality assurance and control.

Metrology in general is traditionally regarded as a key discipline in making industrial manufacture of components possible. In particular metrology enables process control on the basis of measurands either defined on the components or on some specific process characteristics. In this way parts are described using absolute values combined with tolerances. Dimensional metrology covers measurement of dimensions and in principle also geometries based on distance measurements.

In the traditional manufacturing environment, dimensional metrology is an integral part of all quality assurance systems, and the available tools in terms of instrumentation, calibration artefacts, standards and well established procedures all support the increasing demands for production in global networks of highly complex components and products.

In the context of Multi-Material Micro Manufacture (4M) metrology has an extremely important role to play because the manufacturing paradigms taken primarily from the macroscopic world are applied to micro or even nano scaled components and functional features. In contrast to semiconductor processing, where each chip location is known to few tens of nanometers at all times during processing, the 4M manufacturing paradigm has to deal with extremely high positioning and alignment accuracies in-between process steps, where each process not originally was intended to deliver such accuracy. Furthermore, many product concepts are based on assemblies of components, usually manufactured in different ways and locations (as seen in macro scale manufacturing). This concept requires detailed knowledge of not only absolute dimensions and geometrical quantities, but also about the uncertainty of measurement, because this is a decisive parameter when dealing with mating capability in general.

Therefore this paper deals with dimensional metrology in micro manufacturing. It will review different measurement tasks at this scale and also discuss technologies capable of performing measurements. Establishment of traceability and tolerancing will be discussed in the context of micro scaled components and functional features. Based on this, a gap analysis will be presented.
2. Measurement tasks in micro technology

Dimensional micro metrology is in this paper defined as the part of dimensional metrology that concerns measurement and calibration of dimensional quantities on components with at least one critical dimension or functional feature in the micrometer range.

The generic measurement tasks to be performed in dimensional micro metrology are [5]:

- Distance as defined between two surfaces oriented in the same direction. Example: distance between two lines of a line grating or two planes in a microstructure.
- Width as defined by the distance between two opposing surfaces. Example: width of a channel.
- Height as defined by the distance between two surfaces of same orientation but placed in a vertical direction. Example: depth of microfluidic channel.
- Geometry (or form) as defined by the distance between the surface of the object and a predefined reference. Example: flatness of wafer.
- Texture and roughness defined as geometries of surface structures whose dimensions are small compared to the object under investigation. This poses a particular challenge for micro sized objects because the surface becomes dominant with respect to object volume.
- Thickness of layers.
- Aspect ratio as defined by the depth of a structure divided by its width.

Each the above mentioned generic measurement tasks will usually be found in different combinations in real-life microsystems. In the following, examples of measurement tasks in the area of multi-material micro manufacture will be presented.

2.1. Micro Electro Mechanical Systems (MEMS)

MEMS can be defined as small components having both an electrical and a mechanical functionality [6]. Traditionally MEMS have been designed based on the semiconductor manufacturing platform. Traditional MEMS products are usually characterised by higher aspect ratios than conventional integrated circuits. Due to the relatively small absolute dimensions, high aspect ratios pose metrological challenges. Furthermore, the presence of mechanical and moving parts increases the sensitivity towards mechanical deformations due to measurements. Typical measurands are dimensions and step heights as well as surface texture [6]. The geometries under consideration are essentially 2½D, but will contain free-standing beams and possibly also voids and inclusions (example Figure 1).

2.2. Microfluidics

Products for chemical and biochemical analysis of fluid have become a major research topic during the last decade. These so-called lab-on-a-chip components are manufactured both in silicon and polymer material. However, a trend is seen towards polymer based products and therefore new manufacturing schemes are developed. Manufacturing of tools for micro injection moulding and hot embossing of microfluidic systems can be realized by several different process chains. Some are based on combinations of photolithography, etching and electrodeposition, while an increasing amount of process chains based on thermal or mechanical material removal processes are seen [8]. This furthermore increases the obtainable geometrical complexity (going from 2½D to 3D). The replication processes (injection moulding or hot embossing) is complicated by increased geometrical complexity and reduction in component size. Therefore the need for both quality assurance of single components as well as process control has increased.

Table 1 contains an example of obtainable features with different manufacturing schemes thereby also implying the metrological requirements for quality assurance [8]. It is clear that the dimensions of these features range over several decades. Once the tools are finalized and used for replication purposes, the inverse features are produced and the resulting components also subjected to a quality assurance procedure usually involving dimensional metrology. Figure 2 illustrates this principle. Depending on choice of mould making technologies perhaps a master geometry must be made. In principle the same features need to be measured on the master, the mould and the final workpiece, but the fact that they are positive, negative and positive pictures of the features (Figure 2) complicates the measurement task. For example, it is much easier to measure the surface roughness of a vertical wall on the mould that will result in a channel on the final part, than it is to measure the same feature on the final part. Figure 3 illustrates this particular problem on micro channels in master and plastic part.
Table 1.
Comparison of the capabilities of 4 different fabrication schemes for mould inserts for injection moulding of microfluidic devices. Values refer to the average capabilities of the single schemes. Table adapted from [8].

<table>
<thead>
<tr>
<th>Method</th>
<th>Metal</th>
<th>Silicon</th>
<th>Metal or polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photoresist</td>
<td>Advanced Si etch.</td>
<td>Milling or laser</td>
</tr>
<tr>
<td>Geometry</td>
<td>$2^{\frac{1}{2}}$D</td>
<td>$2^{\frac{1}{2}}$D</td>
<td>3D</td>
</tr>
<tr>
<td>Number of layers that can be stacked</td>
<td>1-3</td>
<td>1-3</td>
<td>1-3</td>
</tr>
<tr>
<td>Features accuracy and alignment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XY in µm</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Z in µm</td>
<td>1-5</td>
<td>1-5</td>
<td></td>
</tr>
<tr>
<td>Min. channel width in µm</td>
<td>5</td>
<td>10</td>
<td>20-200</td>
</tr>
<tr>
<td>Max. channel depth in µm</td>
<td>200</td>
<td>500</td>
<td>∞**</td>
</tr>
<tr>
<td>Max. aspect ratio</td>
<td>20</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Surface roughness</td>
<td>Sq Rms in nm</td>
<td></td>
<td>200-300</td>
</tr>
</tbody>
</table>

* For micromilling this value strongly depends on the type of material and feature (concave or convex).
** For micromilling this value depends on the tool diameter.

Real 3-dimensional micro metrology problems occur for example when micro tools for machining have to be verified. The absolute values and variability of the tool's geometrical parameters directly influence the performance of the milling process. Conventional measuring methods face strong limitations already for conventional size milling tools and tool size reduction greatly increases the difficulties in the dimensional and geometrical characterization of milling tools. In [9] relevant properties of micro milling tools are identified and discussed. They include effective tool diameter, cutting edge radius, helix angle rake face roughness. Figure 4 illustrates typical SEM pictures of a Ø 200 µm ball nose end milling tool. In particular the cutting edge radius is crucial for controlling the milling process. It is the experience that critical dimensions of micro tools may vary considerably. Often tolerances of 10-20 % are stated on for example diameters, and variance within such intervals can be observed. Therefore quality assurance is necessary.

2.3. Microtools

In micro manufacturing dimensional metrology is used for quality assurance of components and for process control. Some common characteristics can be identified for the measurement tasks:
- The smaller the absolute scale, the more challenging is the measurement task.
- Large aspect ratios pose difficulties in particular when absolute dimensions are small.
- When geometrical complexity is increased from 2D to 3D features, measurement tasks are complicated.
- If a component contains features differing by several orders of magnitude, metrology usually involves different methods/instrumentation.

Figure 5 shows a proposed illustration of selected measurements tasks. Figure 5 holds no information on geometrical complexity, but as aspect ratios can be derived from the diagram, an indication of some problematic regions is given.
3. Instrumentation for dimensional micro metrology.

The available instrumentation for dimensional metrology at micro scale can be categorised as follows [10]:

- Surface topography measuring instruments (including mechanical, optical and SPM based instruments).
- Scanning electron microscopes (SEM).
- Micro coordinate measuring machines (micro CMMs).
- Other techniques.

3.1 Surface topography measuring instruments

The principal methods of surface topography measurement are stylus profilometry, optical scanning techniques, and scanning probe microscopy (SPM) [10]. These methods, based on acquisition of topography data from point by point scans, give quantitative information of heights with respect to position. Their interaction with the surface under investigation as well as their range and resolution differs significantly. Table 2 shows some merits and limitations of the techniques.

In a stylus profilometer, the pick-up draws a stylus over the surface at a constant speed, and an electric signal is produced by the transducer. This kind of instrument covers vertical ranges up to several millimetres with resolutions as good as nanometric, with lateral scans up to hundreds of millimetres being possible. The interaction between tip and surface gives limitations as to detectable features.

Optical scanning techniques encompass most typically optical profilometers, confocal microscopes, and interferometers. The optical methods are non-contacting which allows measurements on soft surfaces. However, this kind of instrument covers vertical ranges up to several millimetres with resolutions as good as nanometric, with lateral scans up to hundreds of millimetres being possible. The interaction between tip and surface gives limitations as to detectable features.

SPM techniques rely on very low (if any) contacting forces between a very small tip and the sample, resulting in high lateral and vertical resolution. Typically measurement ranges are relatively small (few hundred µm horizontal, below 50 µm vertical).

<table>
<thead>
<tr>
<th>Principle</th>
<th>Merits</th>
<th>Limitations</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stylus</td>
<td>Traceability</td>
<td>Mechanical contact</td>
<td>[6,11]</td>
</tr>
<tr>
<td></td>
<td>Large range</td>
<td>Tip geometry</td>
<td></td>
</tr>
<tr>
<td>Autofocus</td>
<td>Point by point probing</td>
<td>Limited lateral resolution</td>
<td>[6,11,12,13]</td>
</tr>
<tr>
<td>White light interferometry</td>
<td>Fast</td>
<td>Limited lateral resolution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High vertical resolution (sub-nm)</td>
<td>Max. detectable slope appr. 15°</td>
<td></td>
</tr>
<tr>
<td>Confocal</td>
<td>High aspect ratio structures</td>
<td>Limited lateral resolution</td>
<td>[6,11,12,13]</td>
</tr>
<tr>
<td></td>
<td>Max. detectable slope up to 75°</td>
<td>Limited vertical resolution</td>
<td></td>
</tr>
<tr>
<td>SPM</td>
<td>nm resolution</td>
<td>Slow</td>
<td>[14]</td>
</tr>
</tbody>
</table>

3.2 Scanning electron microscopy

Scanning electron microscopy (SEM) is based on scanning an electron beam on the specimen. The electrons interact with the sample and different detectors can characterise physical and chemical properties of the sample surface. Magnification levels cover a wide range with an extremely large depth of field [15]. However standard SEM operates under vacuum, which might be seen as a limitation.

SEM provides nice pictures primarily for qualitative evaluation. However, in a metrology context SEM is most commonly used in a 2D mode for measurement of for example critical line widths etc. in semiconductor industry. In this case, calibration is crucial since the measurement of a 40 nm wide transistor gate requires a bias of less than 4 nm and repeatability in the sub-nm range. Therefore efforts are undertaken to understand influence parameters such as edge effects due to electron beam-sample interaction, electron source tip geometry etc. [16-22].

Despite the large depth of field, SEM pictures are essentially 2D. However, by using SEM in combination with a photogrammetry approach 3D surface data can be achieved as reported in [6,23-30]. This could be a good possibility for very small, hard to access features, although the electron beam needs to be able to reach the surface.
3.3 Micro CMMs

The miniaturisation of CMMs has been the subject of research and development activities during the last 10 years. The results have been smaller frames capable of providing stiffness and thermal stability enough to achieve sub-µm uncertainties for 3D measurements. 3D measurement capability can be identified as the ability to measure features from aside and partly from inside. Many micro CMMs can be found in institutes and universities [31-40], but also some commercially available machines exist, for example by the companies Zeiss, IBS, SIOS, Panasonic and Mitutoyo.

Probe design and manufacture seems to be one of the most critical parts of the micro CMMs. SPM-like probes (cone-shaped tips) are not useful for 3D metrology since they can't probe from aside. Therefore most of the currently available solutions are based on ball shaped tips [41]. Here particularly the probe stiffness is critical, but also stick-slip effects between probe and sample, uncertainty of probe dimensions and form error etc. influence the obtainable accuracy. Solutions based on optical detection [42], laser trapping [43-44] and vibrations [45] are also found.

3.4 Summary

Figure 6 shows a classification of measuring techniques related both to dimension and complexity. In the figure, mechanical and optical surface topography measuring instruments are currently available, but they are relatively expensive and slow. The measurement challenge increases from left to right and from the top to the bottom of the table. The field covered by compact - ultraprecision CMMs is highly relevant in industry. Techniques such as 3D SEM are of great interest, though their traceability is still not well established through universal calibration procedures. There are a few truly 3D metrology systems in the µm and sub-µm domain.

![Fig. 6. Classification of equipment for dimensional micro metrology [10].](Image)

4. Challenges for dimensional micro metrology.

In this section the challenges related to metrology for micro manufacturing will be presented. The section will cover the following aspects:

- Gap analysis based on section 2 and 3.
- Calibration and traceability.
- Tolerancing and specification of micro products.

4.1 Gap analysis

The review of measurements tasks and equipment for micro metrology has resulted in the following observations of gaps and challenges:

- Micro scaled components constitute a very heterogenic group including a large range of different materials, different measurands and of course a large dimensional span. New measuring devices are needed that integrate different measuring principles.
- High aspect ratio applications do exist, but many applications are still with aspect ratios below 2. Nevertheless, small absolute dimensions (<1 µm) pose difficulties for dimensional metrology also with aspect ratios around 1.
- The need for 3D analysis exists and is increasing.
- No real solutions exist for rendering 3D results in a scale below 1-10 µm.
- Probe manufacturing and probe-sample interaction are two major development points.
- In-process capability of the measuring equipment will become extremely important as micro manufacturing is being industrialised.

4.2 Calibration and traceability

The macroscopic world has its own traditions in achieving traceability and normally uses artefacts such as scales, laser interferometers, stepgauges, ball plates, straight edges, optical flats etc. For linear dimensions, gauges or laser interferometers are used, for form measurements some physical artefacts are used. In the microscopic world far less standards are in use: step heights, scales, 2D scales, and for SPM-measurements a crystalline mica or silicon surface is usually considered as a suitable calibration artefact for achieving traceability. However, the available artefacts leave large dimensional regions uncovered. In particular all standards seem to represent low aspect ratios hence no real 3D standards are available in this regime. Physical standards for surface roughness, subsurface properties, form (flatness, sphericity, asphericity) in glass, ceramics and metals are therefore urgently needed. Along with the artefacts, calibration procedures, preferably standardised, should be defined in order to have a common set of rules. International comparisons were conducted primarily in the SPM area [46-47], and relatively good agreement was found for 1D measurements in the plane, whereas height measurements were found to be more problematic.

4.3 Tolerancing and specification of micro products.

Tolerancing is linked closely together with metrology since a general rule of thumb indicates that the measurement uncertainty should be 1/10 of the specified tolerance. It is very hard to comply with this rule when the absolute dimensions are in the µm range,
and therefore exact knowledge about the measurement uncertainty is crucial. As discussed previously very few calibration artefacts and methods exist at this scale and therefore a sound evaluation of measurement uncertainty is difficult. However, a prerequisite is that it is possible to specify a tolerance, and there still is a long way to go with respect to this issue. The ISO GPS-system is set-up with the traditional workshop dimensional metrology in mind. This means that at many places measuring elements are defined as mm-sized, so measuring smaller sizes is not directly possible when interpreting these standards strictly. This goes for surface roughness as well as for dimension, position and form. Some attempts to introduce a function-oriented tolerancing concept for monolithic integrated systems (e.g. MEMS) is given in [48-49]. This concept is however based on the fact that a layer-by-layer manufacturing methodology is applied. If micro mechanical systems are considered within the usual 4M domain, then a complete lack of guidelines exists.

5. Outlook

The current paper has described issues and challenges in dimensional micro metrology with emphasis on the use of metrology as a key discipline in micro manufacturing. Therefore metrology applied for both quality assurance of products and process control is extremely important in micro manufacturing. Identification of measurement tasks and instrumentation is not enough, since a huge amount of research needs to be performed in terms of calibration and establishment of traceability for dimensional micro metrology. Furthermore specification and tolerancing seems unavoidable if industrial scale micro manufacturing is going to be realised.

6. References


[46] “Key Comparison Database” KCDB Appendix B at www.bipm.org

