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ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **59**
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Industrial Metrology and Interchangeable Manufacturing under the Viewpoint of Nanotechnology and Nanometrology

P. Herbert Osanna, M. Numan Durakbasa, Lukas Kräuter

Vienna University of Technology – TU-Wien, A-1040 Wien - Vienna, Austria
E-mail: osanna@mail.ift.tuwien.ac.at

1. Introductory remarks

The increase of quality of technical parts and whole products is not to be connected, of course, exclusively with the increase of accuracy but correlation is given up to a certain extent, particularly if the technical development during the 20-th century is taken into consideration [1]. This trend develops presently continuously further on because of the development from microtechnology to nanotechnology, which means particularly special metrologies and production methods for the realization of manufacturing accuracies in the nanometric range [2]. As the tolerances of workpieces and their features decrease the interaction and correlation between the dimensional tolerances and surface finish becomes more important [3].

2. The increase of product quality based on metrology

Modern production metrology and its industrial application started on the basis of the scientific, technical and organisational work of E. Abbe, A. Michelson, F.W. Taylor and other scientists and experts. After the end of the 20th century – the "Century of Metrology and Quality Control", the development has reached Nanometrology and will proceed to Picometrology. The past forty years have noted the increasing importance of computer aided production metrology as means to control industrial manufacturing, to test technical products with high accuracy on the basis of geometrical product specifications and verification (GPS) and to improve the quality of all kinds of products and processes. Therefore a sophisticated measurement technique must be considered as a very crucial requirement for the production of industrial goods of controlled and optimized quality. This fact played an important role in the improvement of the quality of industrial products and processes. The measurement technique can and must be given a key role especially in modern industrial environment. Essential contributions to increase the quality of products and the productive power of plants can be reached furthermore through the aimed application of measurement methods.

The problematics of the work piece accuracy in modern industrial production technique gained in the last years more and more importance through constantly increasing demands on the quality of the parts produced. The necessity faces the additional outlay caused through the entire manufacturing process, due to the world wide competition struggle and its pressure on the resultant from the maximum economical way and to strive for cost savings in production.

Metrology can be named as an “enabling science” meaning that it is a science which makes other developments first of all possible and it forms the basis for inventions. In operational and industrial environment metrology delivers essential information for the completion of products and about working condition and status of processes. To survive economically also at today’s thoroughly usual short-term changes of the state of the market under worldwide competition, a high quality level of the prepared products together with effectiveness and productivity must be guaranteed, furthermore the reliability at application and employment must be secured; energy losses must be avoided as well for thrifty consumption of raw materials, and finally there are aspects with regard to protection and conservation of the environment of essential meaning.

An excellent explanation of the importance of metrology – although given more than hundred years ago – was formulated by Sir William Thomson, Lord Kelvin (1824-1907): “If you can measure what you are speaking about and can express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers – your knowledge is of meagre and unsatisfactory kind.”

The comprehensive goal of metrology has been clearly formulated by the scientist Galileo GALILEI (1564 to 1642) in the early years of modern times: “Measure everything that is measurable and make measurable what could not be measured up to now”.

3. High accuracy based on precision metrology

At the turn from the 19th to the 20th century there have been various basic inventions in the field of metrology especially as far as geometrical measurements are concerned but also in the field of quality control. To remember the probably most famous highlights of basics and achievements in production metrology and names of their inventors the following can be pointed out:

- E. Abbe 1890: Comparator principle to avoid 1st order measurement errors,
- A.A. Michelson 1893: Michelson Interferometer,
- C.E. Johansson 1896: Parallel gauges,
- W. Taylor 1905: Principle for design of “GO” and “NOT GO” gauges.

It was the area of production metrology where F.W. Taylor realized approximately at the same time the first steps to quality control and therefore also to what one hundred years later has been developed to modern quality management. This of course is explained in a simplified way but nonetheless is in basic industrial reality.

Prior to the industrial revolution, craftspeople served as fabricators and inspectors and were entirely responsible for the quality of their products. Inspection was not a separate function in production. Mass production and the interchangeability of workpieces and parts demanded a new organisation and management in the industrial domain.

The modern philosophy of production – and at the same time the philosophy of production metrology and inspection – was created by the work of F.W. Taylor who has been called “Father of scientific management of manufacturing industry”. By decomposing a job into individual work tasks, inspection tasks were separated from production tasks, which led to the creation of a separate quality department in production organizations and to the tasks of inspection and quality control.

Separate job classifications for inspectors became common in industry. The task of the inspection department was to seek out defective items in production and remove them prior to shipment. Everyone knew that inspection was used simply to ensure that only good products would be shipped, because the pressure from management was for output quantity, not quality. Inspectors became “Policemen” who were to catch “Lawbreakers” – the operators and others who contributed to poor quality of products.

Tens of billions of Euro of sales depend worldwide each year directly on measurement tools and techniques. The appropriate laboratory research provides the measurement bedrock upon which modern society stands. Pocket cellular telephones, air bags, fax machines, video game players these products require length measurements many times smaller than human eyes can see, as well as precision measurements of voltage, frequency, velocity, pressure, radiation, and temperature. Laboratory research continually improves how these basic quantities are measured, a process that is inseparable from each government's constitutional responsibility for maintaining the nation’s weights and measures.

The European and international standardization on quality management systems references to the fundamental and general trend to higher expectations on the quality of products. General experience confirms again and again that it is only possible through continuous efforts and improvements to achieve high productive power as well as high quality production processes and to receive the upright. The quality of the prepared products can thus be seen thoroughly as a fundamental element for the productive power of economic enterprises and in general also for other organizations. Quality affects every aspect of organizations in general and especially of manufacturing organizations and producing factories. Thus, for a product to be successful, the assurance of quality requires a comprehensive systems approach.

In modern factories and industrial companies quality is the responsibility of everyone, from the chief executive officer to the operators on the production floor. People, such as machine operators, assembly workers, ticket agents, nurses, and waitresses are the craftspeople who build quality into products and services. First-line supervisors must provide the motivating climate for employees, direct them in proper procedures, work together with them to locate the problems, and assist in eliminating the sources of error. Middle management must plan, co-ordinate, execute, and monitor quality policy. Finally top management must commit the resources and provide the leadership necessary to set the tone and carry out the requirements of an ongoing, dynamic quality policy.

Product development and product use are customer-oriented activities. The quality effort in these activities should focus on determining customer needs and on translating these needs and requirements into product designs that meet fitness-for-use criteria. The production process includes the physical facilities and information and control systems that are required to convert resources into products. The production process is largely under the control of the business organization. Quality efforts here are oriented towards ensuring that the product conforms to specifications.

The future economic evolution stands in narrow combination with the speed up increase of the quality in the production field. The quality of the products influences the continuity and the rhythm of the production, the production costs, the production extent, the job productivity and the efficiency of these products with their application or their consumption in diverse manner. A high product quality adds to satisfy the needs of the population that are increasing constantly, stabilizing the international cooperation and to enlarge as well as to increase the export ability of the products.

In the first place the extraction of high-quality information is a task of the measurement technology. High product quality can only be achieved when the metrology is integrated tightly into the production events as far as possible. Additionally however, continuously new orders are made through increasing quality of the measurement technology. Because of this quality, the assurance and metrology form an inseparable unit in the process of manufacture.

4. From precision metrology to nanometrology

Since 1970 we have seen the increasing importance of modern metrology as means to control industrial manufacturing and the quality of all kinds of products and processes. At the same time the precision engineering developed as an important trend in instrumentation and metrology. Optical and electronic methods are preferred tools in intelligent production plants. Their efficient use and correct calibration are crucial requirements for quality management in this production environment.

To achieve surface finishes and part tolerances in the submicrometer and nanometer level, it is necessary to incorporate very sophisticated instrumentation and metrology into the design. This development started in the electronics industry, but micro miniaturisation is now of high priority for mechanical engineering too.

Besides microtechnology since 1975 we speak about nanotechnology. The term “Nanotechnology” was introduced by the Japanese scientist N. T a n i g u c h i [4] in 1974 to describe manufacture to finishes and tolerances in the nanometer scale. Extrapolating the specifications from existing and past machine tools, such as precision lathes and grinders, to the new generation of machine tools it was concluded quite correctly that before 2000, the accuracies between 100 nm and 1 nm would be needed to cater for the needs of industry. But Taniguchi was too pessimistic. Whitehouse stated that this has been already state-of-the-art about 1995 [5]. This was and still is based on the development and application of high precision manufacturing processes and on the application of high precision metrology of apart conventional methods (Fig. 1).

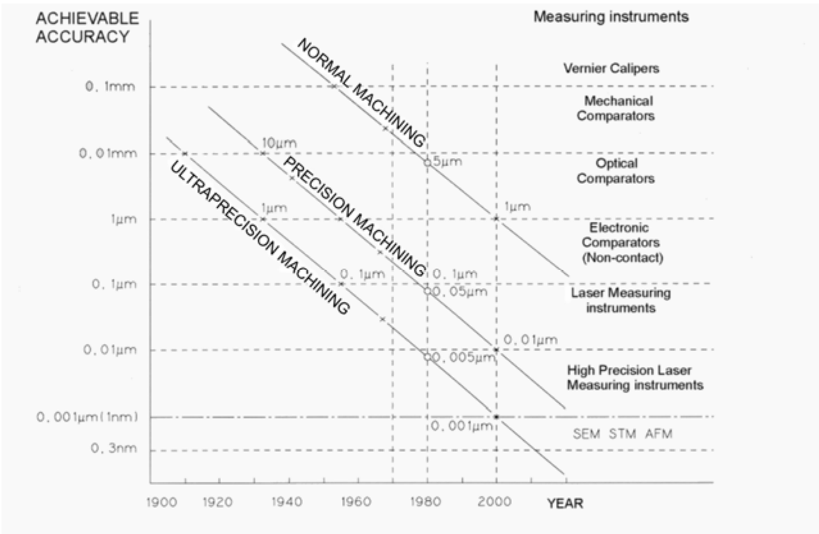

Fig. 1. Development of achievable manufacturing accuracy and dimensional metrology and measuring instruments respectively (N. T a n i g u c h i [4], D. W h i t e h o u s e [5])

In principal, nanotechnology is the meeting point of chemistry, physics, biology, and engineering at the atomic scale. Because nanotechnology in name at least started in engineering it is probably most informative to follow and investigate the subject in this discipline.

Developing from the need to machine as the demands grew in the last thirty years and there came some new methods of fabrication with different materials. Hand by hand with this development the need came to make very accurate machine constructions and to miniaturise sensors and actuators in order to enable the non-intrusive ultra precise control of instruments and production equipment. Also a special demand for quality management is in the point of view in this field.

This trend to increase the accuracy is in line with the development that has been already pointed out in 1960 [1] showing the continuation starting at the beginning of 20th century which is still going on [6] and leads us directly to nano and pico technology.

Because nanotechnology in name at least started in engineering, it is probably most informative to follow and investigate the growth of the subject in this discipline. Developing from the need for more accurate machines as demands grew for example in the fields of compact discs, gyroscopes etc., new methods of fabrication came with different materials. Together with these applications the need came to make smaller sensors and actuators to enable the non-intrusive control of instruments and machines.

In engineering applications, 90 % of transducers are concerned with the measurement of displacement, position or their derivatives such as strain, pressure and acceleration. This has resulted in a mechanical micro world, which has emerged from the technology developed for integrated circuits. Already many small mechanisms are being made, including miniature motors of submicrometer dimensions. Highly reliable accelerometers are already in use. These devices are fabricated on silicon substrates using extensions of such integrated circuit manufacturing processes as photolithography, thin film deposition and the like. Micromotors and articulations are more ambitious but are developed in many parts of the world.

Instrumentation has been developed to explore and measure structure properties at the atomic level. In engineering they have usually been involved with looking at surface topography and boundaries of one sort or another. This requirement goes far beyond the original concept of Geometrical Product Specification and Verification and of the performance of a machine tool or attainable surface texture on a component.

The production of very precise components goes hand in hand with the development of the necessary metrology, and a wide range of measuring instruments has been devised to cater for the evaluation of surfaces and structures down to the 0.1 nm level. Particularly noteworthy are the stylus profilometer, the Nanosurf, the polarizing interferometer, the laser profilometer and the X-ray interferometer. This powerful array of instruments provides a measuring capability which ranges from 50 pm to 15 mm in surface amplitude and from 50 nm to 250 mm in surface wavelength, and techniques for roundness measurements to 1 nm and displacement calibration to 10 pm, traceable to the national standards of length.

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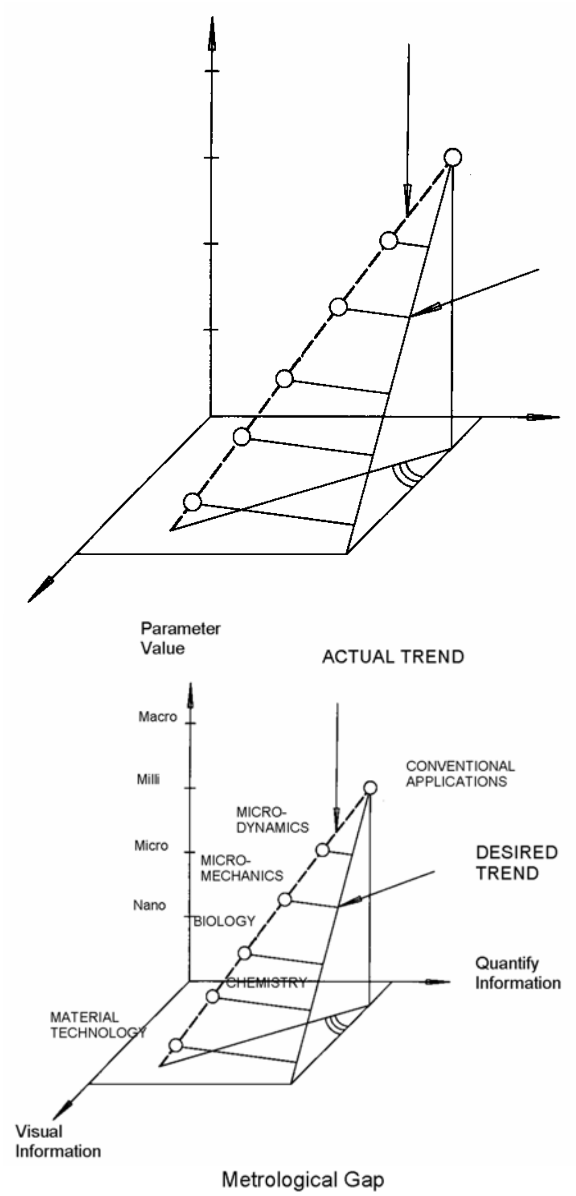

Fig. 2. Metrological Gap (D. W h i t e h o u s e [7])

The reduction in the scale of features or details to be investigated has not necessarily been accompanied by an increase in the ability to quantify. Due to the inability to calibrate at the atomic level of nanotechnology there are difficulties to quantify with sufficient accuracy.

Generally dimensional surface measurement technique has the task to recognize at explored surfaces corresponding details and magnifies greatly in most cases especially perpendicularly to the tested surface to make possible distinctions between individual lateral details. In nanotechnology and precision machining however very small crystalline structures, molecular and atomic assignments are of special interest.

Increasingly those developments have attained since about 1980 at meaning to improve the resolution of the measurement instruments to an atomic level. This will be pursued in future still increasingly, further however also to reduce measurement time as well as uncertainty and to increase precision.

Extremely high accuracy demands deposit presently already at highly developed instruments for everyday use and high technology products in general. The fabrication of these require high precision measurements of length, voltage, frequency, velocity, pressure, radiation, temperature etc.

Laboratory research continually improves how these basic quantities are measured, a process that is inseparable from each government's constitutional responsibility for maintaining the nation's weights and measures.

In persecution of this aim since about 1982 new high resolution and high precision measuring devices have been developed [8, 9]:

- Scanning Tunnelling Microscopy (STM);
- Atomic Force Microscopy (AFM).

For highest demands these methods make it possible to explore atomic structures and generally very accurate and small industrially produced parts and structures. Special variants of these instruments which usually involve specifically prepared specimens and probes are thermal conductance, near field optical evanescence, electrostatic force and magnetic force microscopes.

5. Nanometrology for Mechanical Engineering

5.1. New Developments

During the last few years nanotechnology has changed from a technology only applied in semiconductor industry and in research laboratories to a technology that becomes also interesting to many applications in traditional branches of mechanical engineering. The dramatic improvement of ultraprecise manufacturing machines and the invention of new production techniques like Focused Ion Beam Technology has made the production of features and functional elements with micro- and nanometer size possible and economically reasonable. In metrology, the further development of the above mentioned microscope techniques and especially special variants and related techniques has helped to establish nano metrology in research institutes and meanwhile industrial application has been taken into consideration too.

Although both manufacturing technology and measurement instrumentation fulfil in principal several of present demands in micro- and nanotechnology, international measurement standards in nanometrology are still missing. These standards, including the calibration of instruments, the toleration of form and functional elements in the nanometer scale, new parameters and measurands for nano metrology and guidelines for reproduceable and comparable measurement results are vital for the acceptance of an industrial nano metrology in industry.

Nanometrology is beginning to establish itself in the production process. The needs of the industry for ultra-high precision engineering and workpieces with a surface roughness less than few nanometers call for measurement instrumentation that can be applied reliably in modern production processes, together with international standards defining parameters and tolerances in the nanometer scale.

The requirements on the measurement systems and the measurement strategy to determine suitable parameters, time, costing and the guarantee of a predetermined process stability by means of measurable and correlated parameters come into focus. Now a minimum amount of measured quantitative parameters (which should be correlated to the function of the workpiece) is important.

5.2. Nanometrology demands in mechanical engineering

On basis of industry needs, the demands on industrial nanometrology can be subdivided into three major scientific and economic attributes (Fig. 3).

5.2.1. Major scientific attributes

- Reliability:

Measurement results have to mirror the real surface structure and statistic and systematic errors may be reduced to an absolute minimum.

- Comparability:

Measurement results must be comparable when they are measured with different measurement systems of the same kind. Ideally measurement results taken with different systems should be comparable too.

- Reproduceability:

Several measurements of the same sample under the same conditions must result in the same results. Changes in measurement conditions must result in comprehensible changes in the measured parameters.

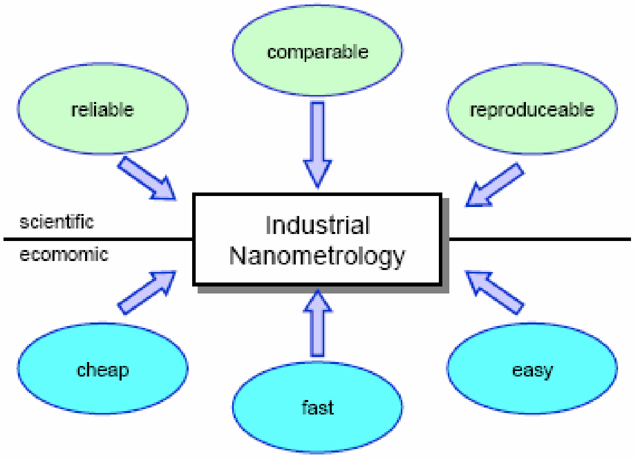

Fig. 3. Demands on industrial nanometrology

5.2.2. Major Economic attributes

- Low costs:

Purchase and maintenance of a measurement instrument must be economically reasonable. If it is too expensive, functional testing will still be more favourable.

- Speed:

The big disadvantage of most measurement systems is the necessary measuring time. Optical microscopes do not reach atomic resolution but they measure very fast, unlike scanning probe microscopes which need to scan line per line over the whole measurement area to get the data.

- Simple handling:

The optimum for a measurement in the production is a full automation of the whole measurement process. Especially handling of the workpieces is extremely difficult in nanotechnology and should be avoided wherever possible.

6. Steps towards industrial nanometrology

The intention to introduce industrial nanometrology into production processes is to save costs, to improve the workpiece quality and to ensure the process stability. To reach these goals and thus to come to a more economic production, a closer cooperation between industry, manufacturers of measurement instrumentation, national research institutes (e.g. NIST, PTB) and national standards organisations (e.g. ASME, BSI, ON, DIN, SNV) but also international ones (ISO, CEN) is necessary. This closer cooperation has to focus on the following five points.

a) Measurement Instrumentation

Principal requirements for measurement instruments used in production process are:

- Reduction of measurement time;
- Automation of the measurement process;
- Self-calibration and self-monitoring;
- Integration into the manufacturing process.

When these requirements are transformed into practice, it will be possible to replace partly functional testing at the final end of a production process by an effective measurement in an early stage of manufacturing. This leads to early failure recognition and reduces defective workpieces.

b) Calibration and Calibration Standards

Calibration standards are still missing in nanometrology. Manufacturers of Scanning Probe Microscopes provide the users of their microscopes with their own calibration samples. Comparable testings of different microscopes and reliable measurement results are still not possible. To ensure a reliable exchange of measurement results, calibration standards have to be defined and manufactured by national standards organisations (in close cooperation and accordance).

Summarising the demands on calibration standards in nanometrology, it can be stated as follows:

• definition of calibration standards for different measurement instruments in nanometrology by national standards organisations;

• build-up of institutions officially certified for the calibration of measurement systems in the nanometer scale;

• manufacturers of measurement systems do have to calibrate their microscopes with officially certified calibration standards.

c) Tolerances and Tolerability at the Nanometer Scale.

The functionality and performance of a workpiece or a mechanical micro- or nanosystem is closely connected to the indicated tolerances. If they are too narrow, the costs of manufacturing will raise although there is no improvement in performance. If the tolerances are too big, the functionality of the manufactured parts can not be ensured.

There exists a dependency of function, machining process, measurement process and the required tolerances and parameters.

Until now, there is no tolerance system for tolerating features and functional elements with sizes in the micro and nanometer scale. This leads to a toleration by personal experience and practical knowledge instead of applying scientifically ensured results and standards defined by international standards organisations. Furthermore it is still not clear which features and functional elements in nanotechnology are to be toleranced. Form and function of micro- and nanoparts differ from conventional parts used in mechanical systems. So the principles and strategies for tolerating features and functional elements have to be adapted to the required performance, the production processes in nanotechnology and the available measurement instrumentation [10].

The necessary improvements can therefore be summarised as follows:

• definition of new tolerance systems designed for the needs in micro- and nanotechnology;

• evaluation of the tolerability of features and functional elements in nanotechnology;

• strengthening the dialogue between design and manufacturing engineers to ensure a useful toleration of features and functional elements in nanotechnology.

d) Parameters and Measurands in Nano Metrology.

Manufacturing on atomic scale is only possible, when physical, chemical and material dependent properties of the workpieces are taken into consideration. This means that new parameters and measurands (e.g. crystal lattice, point defect density, shifting) are getting important, whereas the significance of roughness parameters like RMS and Ra decreases.

For the revision of present standards and the specification of new standards, those parameters have to be taken in account.

To avoid confusion because of an accumulation and a rush of new parameters in nanometrology [11], a meaningful classification of the available and measurable parameters is necessary. Parameters can be classified in three groups by means of geometric, functional and machining properties. Only the parameters relevant for the performance of the functional element or system are measured, applying a measurement strategy that ensures a minimum of parameters and measurands [12].

In other words, industrial nanometrology relies on the following improvements:

• new parameters (crystal lattice, point defect density, shifting) must be taken into account;

• revision of existing parameters and measurands concerning their use in nano metrology;

• classification of parameters in geometric, functional and machining properties;

• definition of measurement strategies to reduce the measured parameters to a minimum and to ensure, that the measured parameters correlate with the functionality of the workpiece;

• assessment of features and functional elements only by quantitative parameters, not by a vision driven inspection of the surfaces.

e) International Standards for Nano Metrology.

Several international standards which refer to roughness, waviness and toleration are more than ten, partly even twenty years old. In the last ten to twenty years new and improved technologies of ultraprecise manufacturing enabled industry of today to produce workpieces of inconceivable sizes and forms. Surface roughness is reaching atomic dimensions and can be measured by sophisticated microscopes like Atomic Force Microscopy. Although the machining and the metrology is able to handle atomic dimensions, rules and standards for those dimensions are not in sight. Due to the lack of adequate standards for roughness and toleration of workpiece elements, existing standards are still in use, even though they are not appropriate for nanometrology.

A feasible approach to new international measurement standards for roughness and toleration on the nanometer scale would be the adaptation and transfer of the GPS (Geometrical Product Specifications and Verification) to nano metrology. The GPS Technical Committee of ISO was established in June 1996 with the aim to create a “Masterplan” which summarizes all existing geometric standards [13]. In this masterplan there are the 18 most important geometric parameters listed, each of them with the appropriate standards. Similar to this approach in conventional geometric metrology, a masterplan for the most important geometric parameters in nano metrology could be designed and then serve as the basis for the definition of new international measurement standards in this area.

7. Summarisation and concluding remarks

In modern metrology it is possible to use instruments capable of creating atomic resolution images of the surfaces of different specimens. AFM and STM are such advanced measurement technologies. At the atomic level metrology and fabrication are closely related. STM has made possible the first steps of atom manipulation which may perhaps lead in the future to fabrication at the atomic level [14]. As a still more futuristic development this may perhaps make possible the design and production of miniature measurement instruments or devices for medical treatment or operations in human beings that might perhaps operate autonomously in the micro or even nano world.

To be realistic the application of atom manipulation for technological purposes is, in the early years of the 21st century, far beyond sensible consideration. The speed and reliability that can be achieved make any idea of mass manufacturing, now, or in the foreseeable future, completely ridiculous.

But in any case nano metrology has become technical reality and pico and femto metrology will not be impossible in the future.

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Промышленная метрология и взаимозаменяемое производство в аспекте нанотехнологии и нанометрологии

П. Херберт Осанна, М. Нюман Дуракбаса, Лукас Кроутер

Университет технологий, A-1040 Виена
E-mail: osanna@mail.ift.tuwien.ac.at

(Р е з ю м е)

Повышение качества технических деталей и продуктов не обезательно связано с увеличением точности, но существует известная кореляция, тем не менее, если обсуждается техническое развитие 20-ого века. Это направление разработывается благодаря развитию областей от микротехнологии до нанотехнологии, что означает применение специальных методов метрологии и производств для реализации производственной точности в нанометрических масштабах.

В работе представлено значение нанометрологии и нанатехнологии для научного развития и производства, влияние на техническое развитие и на высокую точность, а также и в других аспектах человеческой жизни. Техника измерения высокой точности и метрологии имеет основную роль в современном производстве. Применение нанометрологии может значительно повысить качество продуктов и производственную мощность. Сегодня мы встречаем нанометрологию только в научных разработках и в исследовательских лабораториях, но авторы считают, что в близком будущем она будет интегрирована и в контроле качества промышленного производства 21-ого века.