Production Metrology – Future Trends and Challenges

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Developments at the field of production technologies are mainly influenced by mega trends like the scarcity of resources and the globalization. A working group of the German association for measurement and automation techniques of VDI/VDE (the Association of German Engineers) analyzed the demands and trends on the field of production metrology and derived spheres of activity for further research and development work. The paper will give an overview about the results of this working group and shall contribute to the discussions in the international metrological community.

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NOMENCLATURE

CMM Coordinate measuring machine
iGPS infrared Global Positioning System
ITRS International Technology Roadmap for Semiconductor
CD critical dimension
Pdf Probability Density Function

1. Introduction

The developments at the field of production technologies are mainly influenced by mega trends like the scarcity of resources and the globalization of markets. The need for technologies which enable a flexible and efficient production steadily increases. Most important influencing factors are the demands of customers which have to be balanced with market fluctuations and a directed application of resources [1,2]. Above all, the importance of a versatile production was made clear with the economic situation caused by the global financial crises. To obtain a competitive edge, companies have to react flexibly on market fluctuations. The production metrology influences strongly such adjustment processes because it delivers essential information for increasing the transparency of production processes and consequently builds the basis for a flexible and efficient production. If production metrology is applied efficiently, manufacturing within the business optimum is possible by using the obtained information for the adjustment of production steps as well as for the improvement of process planning and product developments. Therefore a change regarding the profitability of production metrology and the direct integration of measurements into production processes is required.

In a working group of the association for measurement and automation techniques of VDI/VDE, consisting of engineers and scientists, the demands and trends of production metrology were analyzed. Resulting from this work, the roadmap “Production Metrology 2020” (Fertigungsmesstechnik 2020) [3] was published in April 2011. Fields of interest are the demands of production, developments at nano, micro and macro metrology as well as the approaches for measurement uncertainty estimation, the integration of measurement systems into production and the profitability of measurements.

To discuss main results of the roadmap two differing examples are covered in this paper: the production of components for wind power plants and the production of semiconductor devices. Both industries differ in their demands which have to be focused by the respective production metrology. Due to small batch production of highly demanding components of wind power plants, the optimized and efficient application of standardized measurement processes is not possible. In contrast the main demands of the semiconductor industry are to perform measurements in micro or nano scale with adequate measurement uncertainty and acceptable effort.

2. Metrology for nano and micro production

Nanotechnology deals with the production, characterization and application of features, which have at least one dimension at the nanoscale, i.e. between 1 and 100 nm. A well-known high-volume industrial production process of nanoscale features with very tight tolerances is semiconductor manufacturing. In 2010 e.g., integrated circuits like CPUs with 32 nm CD (critical dimension) were introduced and prototype processes for production of the 22 nm technology generation were developed. Overlay specifications below 10 nm are already required in current semiconductor production and these small tolerances have to be guaranteed by the lithography wafer scanners at wafer throughput rates of more than 150 wafers (300 mm) per hour. The current and future requirements on the patterning as well as metrology tools needed for mask and wafer production are described in the well-known ITRS, the International Technology Roadmap for Semiconductor [4]. For example, the ITRS uncertainty specifications for metrology tools to be used for dimensional characterization of feature size (CD) and feature coordinates on transmission photo masks are already in the sub-nm region. In order to approach these specifications a full understanding of the response of metrology tools to feature variations is indispensable. If this understanding based on physical modeling of the measurement process is available for the most important process control tools which are in use today, like SEM, AFM or scatterometry results of these different classes of instruments could also be compared on the required sub-nm level.

The application of nanoparticles is another important field in nanotechnology. Often the intended impact of nanoparticles is critically dependent on their size and size distribution. A reliable particle size metrology is thus needed for industrial quality control of these parameters, which also has to take into account their different environments (aerosols, liquid suspension, on substrates).

The production of microsystems and their components puts additional challenges on metrology. Here we only mention briefly the high aspect ratio of microsystems features and their sometimes challenging mechanical properties. Multi-sensor measurement techniques (e.g. optical and tactile sensing) are typically needed for a full characterization of microsystems.

The following general development trends are foreseen in micro and nano metrology: improved modeling of measurement process allows to reduce measurement uncertainties and to ensure comparability of different instruments; comprehensive data evaluation techniques will further be developed (e.g. for 3D roughness parameters); multi-sensor techniques and development of new sensing principles will allow a full characterization of the functionally important parameters in industrial quality control; in-line metrology will become even more important for process control; “virtual instrumentation” which supports calculation of task specific measurement uncertainties will become more widespread; for full 3D characterization at the micro and nanoscale the potential of tomographic methods will be further evaluated.

3. Metrology in macro scale production

With macro scale the measurement of features exceeding 1 mm is focused. There is an obvious trend to increase the size of features but with tightening of tolerances. Hence, the producers of components for e.g. wind power plants are fronted with highly demanding products and increasing product variety. The applied production metrology for macro scale features cover measurement systems with material standards like NC coordinate measuring machines (CMMs) or systems with optical standards like laser tracker, tachymeter or optical CMMs as well as the standardized manual measurement devices and specialized measurement systems [5]. Besides, different applications are established, from stationary devices to mobile measuring systems which offer high flexibility and enable the direct use in the production environment.

Several interesting developments like large volume coordinate measuring systems (e.g. laser tracker, iGPS) enable new scenarios for applications which exceed the previous application for product inspection [6]. Further developments at the field of macro scale measurements include the increasing variety of measurement systems, ongoing reduction of the measurement uncertainty while increasing the level of integration into production processes. To face deficits like the environmental conditions and missing strategies for efficient application the research and development activities have to be focused on mobile measuring systems, the minimization of measurement uncertainty, navigation in production environment with global coordinate systems as well as the digitization of workpieces, machines and plants.

Due to developments of new robust measuring systems using standards based on electromagnetic waves, like the Lasertracer or the iGPS, generating large coordinate systems with adequate measurement uncertainty will be possible.

3.1 Highly demanding products

The importance of alternative energy resources rises. Especially wind power plants are a serious business where cost efficiency, life cycle costs, reliability and availability of the components must be considered.

Gear Boxes are a major part of all wind turbines. The quality requirements are high: as the wind blows in gusts, a backlash-free operation is indispensable to ensure a long and beneficial lifespan of the system. Mechanical efficiency is directly related to economic efficiency. Noise reduction in the gear box is important to ensure the public acceptance of wind turbines. Only few manufacturers are able to produce such large gear boxes, and now they have to deal with serial production, having many unknown requirements for quality in very large dimensions.

Gears, bearings, and housings have to be produced with tolerances down to 1/100mm and below – on components with up to 4m in diameter. Bridge coordinate measuring machines play a vital role in ensuring the quality of these components [7]. They can reach features that are difficult to access for example on spiral gears with small module. Optical instruments that require a straight connection between the optical sensor and gear’s surface are often limited by these requirements. Gear testers that typically use a precise rotary table are not able to carry the heavy gears [8].

Fig. 1 shows a large bridge coordinate measuring machine performing measurements on gear components for wind power plants. The figure also shows an example for the demanding requirements concerning accuracy by comparing tolerance ranges for gears in automobile transmission and wind turbines. Improvements of the mechanical machine structure trough finite element based design and software correction of machine deviations lead to a reduction of two-thirds of machine’s length measuring deviation within the last 20 years since the beginning of coordinate measuring machines use. Length measuring deviations below 5 µm for 1 m measuring length on machines with a measuring volume in the range of 25 m^3 are possible today. Further improvements can be expected in future. The effect of machine improvements on application accuracy depends strongly on control and compensation of environmental influences.

Fig. 1 Demanding measurements of gear components for wind turbines on bridge coordinate measuring machines

3.2 Production metrology enables global production concepts

To close control loops of production processes measured data have to be applied. If processes become more complex because of linking of several production steps, many companies are faced with a big challenge. The application of control loops close to production requires valid data as well as rules for decisions which are essential for the process controlling. Hence, the development of technologies and methods to capture the production systems as a whole with less effort is needed.

One promising approach is offered by global coordinate systems which enable the simultaneous measurement of position and orientation of workpieces, machines and operators as well as product features. To increase the absolute positioning accuracy of robots the iGPS was developed with the possibility of extending this approach to complex production scenarios. The iGPS is based on triangulation and enables the simultaneous position measurement of several sensors in a measurement volume exceeding several meters.

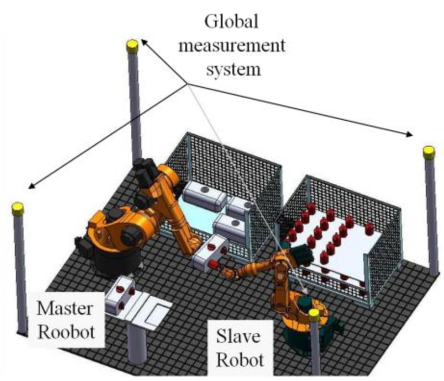

Fig. 2 Setup of two cooperating robots for mounting processes

Fig. 2 shows the application of the iGPS for robot based mounting processes. The positions and orientations of both robots are determined. This information enables the automatic readjustment of the master robot position and the positioning of a second robot in reference to the master robot. This principle can be transferred to complex production processes where the control of production processes is enabled as well as the fast reaction to process disturbances. Therefore, the correction values have to be determined based on valid data of the global coordinate system and control strategies.

Needs for developments are the combination of several sensors with different measurement principles in one global coordinate system. To obtain a high density of information the increase of measurement frequency is essential.

4. Concepts for integration

By nature, production metrology has to be included into the production itself. It cannot stand for its own. Here, opportunities and concepts arise from the immediate integration of production metrology in the process to be measured.

On the one hand, production metrology enables the assessment of the process itself (process related quality assurance). On the other hand, it can be used to capture the quality of the resulting product (product related quality assurance). In terms of a quality control loop, production metrology establishes the measuring element for quality assurance.

In this context, the focus of production metrology will be shifted from a rather product related quality assurance to a more process related quality perspective. This is due to the fact that high-quality products can only be produced with optimal production processes. Therefore, process related quality assurance implicitly establishes the foundation for error-free products.

A commonly seen trend in production metrology is towards inline inspection, where production metrology is a fully integrated and synchronized component in the production chain. Thus, measuring equipment moves closer to the production process, making quality control loops smaller and enabling a more direct use of measurement results.

Particular challenges within the integration of production metrology arise from the necessary linkage of production engineering and production metrology: The increasing individualization in production requires in consequence a more flexible production metrology (e.g., with respect to measuring points and uncertainties). The systems involved in production metrology must offer a high degree of interoperability with the connected production technology (e.g., process control, machine control). Since state-of-the-art production metrology features an increasing number of components and process interfaces, it also has a higher complexity in comparison to usual metrology systems. This increasing complexity of modern production metrology puts high demands on producers and users of such systems with respect to qualified personnel and investments. At last, the increasingly necessary computer technology becomes outdated quickly, especially in comparison to other means of production.

With regard to the integration of production metrology, several trends spanning various sectors of industry can be identified: 100% inspection gains importance, since increasing demands for product quality in individualized production can only be realized by an individual inspection. This requires that the data acquisition and the subsequent data evaluation are both synchronized with the production cycles. Quantitative production metrology replaces qualitative inspection. The transition from an ok/not ok inspection to a quantitative quality assessment implies that suitable quantitative quality features can be defined. In this context, recent research is concerned with the question on how expert based quality assessment (e.g., related to apparent product features or its aesthetic appearance) can be automated using production metrology [9,10]. The knowledge on production processes and their influencing parameters increases. Here, insights from many areas of science are helpful, e.g., for the generation of analytic or data driven models or for the application of methods from pattern analysis. Within this development, methods of monitoring and diagnoses are being enhanced, such that statements can be made on the process status and necessary maintenance measures even for complex production processes. In consequence, production metrology itself contributes to widen the understanding of production processes. Systems of production metrology become multisensory. In doing so, the resulting quality assessment on basis of several information channels promotes the significance and reliability of quality control. An essential prerequisite is that inexpensive standard sensors, which can be applied universally due to standardized mechanical, electrical and information interfaces are available. Sensor technology and data evaluation converge. So called “intelligent” sensors integrate a certain part of the data evaluation together with the actual measurement sensor into a single device. That way, measurement systems instead of single measurement components inevitably come in the center of attention. Production metrology becomes an indispensable part of quality control loops.

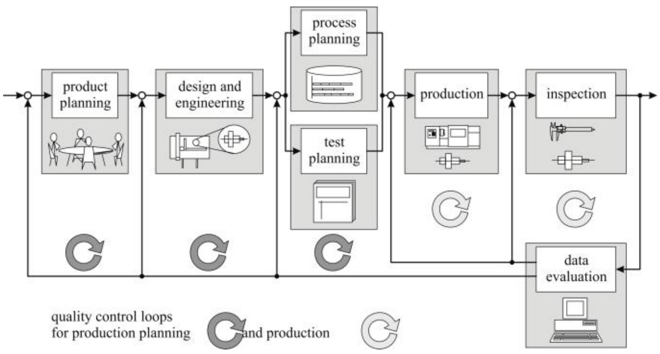

Fig. 3 100% inspection together with small quality control loops provide for optimal expenses and benefits [11]

The direct feedback of measurement results on the production (the small quality control loops in Fig. 3) is a prerequisite to obtain the advantages of 100% inspection together with optimal expenses and benefits. Associated with the system technology aspect of such control loops, fast reacting systems with as short as possible time constants are of increasing importance to minimize costs related to defective products or rejections. Reconfigurability, adaptability, and learning capability of production metrology increase. This trend can be traced back to the increasingly individualized production which requires that production metrology adapts itself to varying inspection tasks or can be easily customized. Therefore, measurement systems must have the capability to automatically identify the process or the product to be measured and to adjust the measurement parameters in an optimal way. Operation and service of production metrology becomes easier, since technically oriented operation concepts are replaced by more human centered concepts. That way, both the efficiency of the overall metrology system rises and undesired influences on the measurement result stemming from different skills of different operators are reduced. The robustness of systems of production metrology increases. This is particularly necessary for inline inspection to make the measurement result independent e.g. of varying environmental conditions and operators and to ensure its integrity. The necessity to prove the process and product quality increases. Besides aspects of product liability and machine safety, intra-company assignments of quality responsibilities to sub-processes are relevant. In order to provide this proof in the long term, objective procedures with quantitative quality parameters must be employed and validated. Such procedures can be defined e.g. by means of appropriate guidelines (see e.g. [12]) and certifications.

In conclusion, the integration of production metrology imposes several considerable challenges. However, the current trends suggest that production metrology is able to guarantee the necessary high quality of production and products.

5. Measurement uncertainty

The importance of measurements for process control in manufacturing systems started to grow in the end of the 19th century. In the globally operated production systems of today worldwide accepted standards for traceability of measurement results to the SI, the International System of Units as well as guidelines for determination of measurement uncertainties, like the guideline for the expression of uncertainty in measurement (GUM, [13]) are indispensable prerequisites for worldwide comparability of measurements. Normally all relevant features of products are characterized by suitable measurements and on their results decisions are made which influence the production process and thus the final quality and value of the products. This topic is becoming even more important for an industrial production in which increased product quality is combined with smaller manufacturing tolerances and more precise production methods.

The procedure described in the GUM for determination of measurement uncertainties basically consists of the following main steps: a) description of the state of knowledge about the measurement, b) modeling of the measurement process, which includes the functional relationships of the measurand with all relevant influence parameters and the measurement result, c) evaluation of all influence parameters by assignment of suitable probability density functions (pdf, determined by either type A or type B methods), d) combination of the expectation values of the input parameters and their associated measurement uncertainties on the basis of uncertainty propagation laws, e) calculation of the so-called expanded measurement uncertainty, which corresponds to a confidence interval for a given confidence level (e.g. 95%), f) specification of the full measurement result which consist of the best expectation value of the measurand and the associated expanded measurement uncertainty.

Usually the modeling of the measurement is the most difficult part of the uncertainty analysis and requires a good understanding of the whole measurement process. An extension to the GUM was published recently [14], which describes the use of Monte Carlo methods for calculation of the propagation of pdf’s in complex model systems circumventing limitations of the GUM which dealt with linearized model equations only. This method was already successfully applied in the so-called virtual CMM software for determination of task specific measurement uncertainties of coordinate measurement machines (CMM).

In the international standard ISO 14253-1 [15], it is described that the measurement uncertainty of an instrument used to characterize product features reduces the specified manufacturing tolerances for these features. In case no other arrangements have been made between supplier and customer, the tolerance scheme of ISO 14253-1 [15] is valid. This also means that the measurement uncertainty for the testing of product features has to be made according to the GUM procedures.

A full GUM compliant measurement uncertainty analysis can be a demanding task, depending on the complexity of the measurement process. In order to increase the practical applicability of the GUM in industrial process control, some guidelines for qualification of measurement processes, like e.g. the VDA 5, have combined the standardized experimental procedure of measurement system analysis with the requirements from the GUM, however in a simplified form.

Future trends in measurement uncertainty analysis which are foreseen are a more widespread use of the measurement uncertainty concept in industrial process control, the development of test and certification procedures for virtual instrument software for calculation of application specific uncertainties, and as a result to take into account the impact of the measurement uncertainty of the metrology tools used for production control and product feature characterizations already in the product design phase.

6. Profitability of and with production metrology

Mostly, the applications of production metrology to assure the product quality are assumed to cause only costs. These cases do not consider the costs for errors which are avoided by measurements. This perspective avoids the efficient application of production metrology as a basis of the economic production controlling [16]. The main causes of this understanding are the theoretic approaches of the economic science, that differ between value-adding and supporting activities. The production metrology is modeled as a supporting activity and does not contribute to the added value of products, from a theoretical point of view. To investigate the added value of measurements is very difficult and is afflicted with a high uncertainty. Due to this, to determine the amount of expenses for errors is nearly not possible or rather requires precise process models. Hence, the added value of production metrology is neglected. Whereas, the purposeful application of production metrology contributes to the minimization of production costs. With this the production within the economic optimum is enabled because of the generated knowledge which makes an improvement of production processes possible [17,18].

To achieve that goal, the benefit of the generated knowledge by measurements has to be quantified by the cost accounting. The main challenges are to estimate the costs dependent on its causes and to evaluate economically the benefit of measurements. To estimate the costs for investigations and operating concerning its application, the approach of a process oriented cost accounting is useful [19]. The performed service of measurements is allocated to its process steps. Hence, the attribution of whole cost for production metrology to the overhead costs can be avoided.

The estimation of the economic benefit of measurements is very difficult and currently not yet solved. The quality and reliability mainly influences mainly the customer satisfaction and therewith the success of the company. It is difficult to quantify these “soft” factors. Hence they cannot be considered by the cost accounting. To solve this conflict, the effect oriented quantification of costs is possible. With this approach cost of conformity and nonconformity are distinguished. Only the quantification of the benefit of measurements contributes to their objective evaluation and enables the decision for investments. [19,20]

Besides the estimation of costs for measurements, the balancing between costs for production and costs for measurements is essential. The application of production metrology at the right position in a process chain is equally important as the design of the measurement process. To make clear decisions about the results of manufacturing and to optimize the processes against costs for manufacturing and measuring, requires a multidimensional view of these processes (Fig. 4) [20].

These decisions depend on several factors like the observed process distribution which results from the real process distribution and the uncertainty of the measurement process. Production processes with a high distribution require a small measurement uncertainty. Otherwise, having a well known process with small distribution, the measurement uncertainty can be bigger considering the relation between observed distribution and tolerance. This approach is useful if the costs for decreasing the measurement uncertainty seriously exceed seriously the costs of the manufacturing process.

To optimize the costs for manufacturing and inspection, both parts of the costs have to be balanced (Fig. 4) [20].

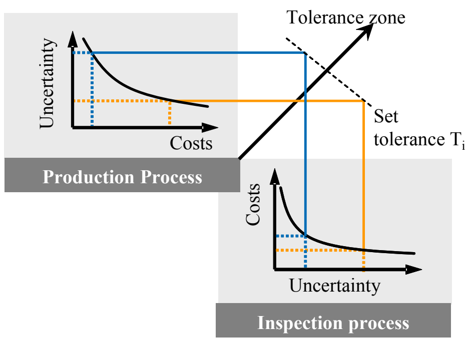

Fig. 4 Balancing the manufacturing and measurement process against costs and uncertainty.

7. Conclusion

The trends of production metrology are influenced by the demands of production and benefit from the steadily increasing variety of measurement technologies at the nano, micro and macro scale. Above all, optical technologies are developed continuously without eliminating classical, well known and capable, technologies like CMMs. Within the “Roadmap Production Metrology 2020”, a variety of trends is focused and summarized with the keywords “faster”, “more precise”, “safer” and “more flexible”.

By increasing the number of applications for e.g. optical technologies based on miniaturized sensors, the time of data acquisition can be decreased. Besides, the integration of measurements close to production increases. Above all, the production of highly demanding component for e.g. wind power plants or semiconductors, show the importance of the discussed trends in production metrology. While the increasing minimization requires faster and more high-resolution measuring systems with improved comparability of results the measurement process for macro scale components with small batches have to be optimized against flexibility and adequate uncertainty. By focusing consequently in research and development on the presented topics, the production metrology will be lead to meet current as well as futue demand of production technology.

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