Novel Developments in Dimensional Nanometrology in the Context of Geometrical Product Specifications and Verification (GPS)

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Abstract:
Adequate knowledge in the areas of intelligent coordinate metrology and design are important presuppositions to achieve waste free production and low costs of manufacturing with higher quality and accuracy at the same time. This is of extreme importance in present time of worldwide international competition in industry and production and at the same time increasingly higher costs of energy and raw material.
The prescription and consumption of material and energy to achieve the necessary and required workpiece accuracy in series manufacturing depends to a great extent from the (geometrical) workpiece tolerances of any kind (roughness, form, positional, dimensional) which are prescribed for the production and the fulfillment of these tolerances and therefore for the function of the produced workpieces and their fitness for practical application and none the less of the economy of production altogether. This requirement is of great importance at the time being which is characterized as described above.

Keywords: *precision metrology, design, manufacturing, workpiece tolerancing*

1. Introductory Remarks

If the workpiece geometry of machined parts is considered as a whole there exist interactions between the different features forming the periphery of the part. But also within the surface of every single feature there exist interactions between geometrical deviations of different kind and different order. If we take these deviations of dimensions, roughness, form and position collectively the existing interactions are significant for the accuracy, high quality and the functions of the parts that should be accomplished during practical application. The most important parameters in determining the suitability of a technical part are its compatibility, functionality, performance and corrosion resistance. The precise assessment of wear, friction and miniaturization demands creation of nanometer scaled surface structures, surfaces with thin film deposition and ultra precision surface treatment with the utilization of new manufacturing and measurement instrumentation and techniques. These include micro and nanofabrication of surface patterns and topographies by the use of laser machining, photolithographic techniques, and electron beam and colloidal lithography to produce controlled structures on technical surfaces in size ranging from 10 nm to 100 μm. At the time being 3D surface measurement is already proved to be an important tool in several areas of surface analysis including wear, indentation, topography, contact problems and functional behavior of surfaces (see Figure 1).

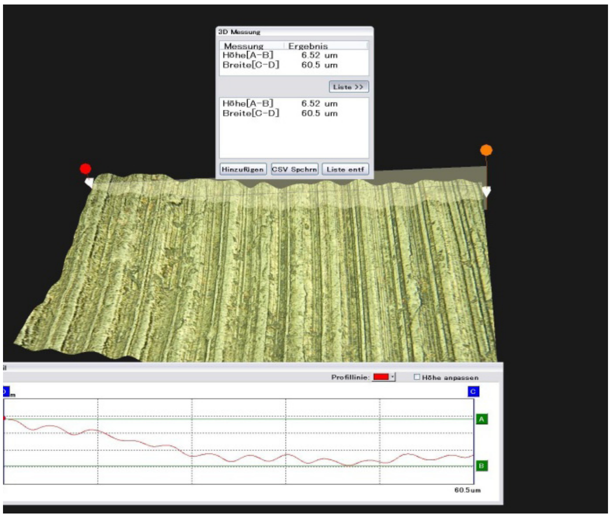

Fig. 1. 3-D observation of a machined workpiece surface using a digital microscope [1]

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 engineering, 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.

2. Intelligent Design and Advanced Measurement Techniques

As the tolerances of workpieces and their features decrease, the interaction and correlation between dimensional tolerances and surface finish become more important [2, 3]. To achieve surface finishes and part tolerances in the sub-micrometer and nanometer level, it is necessary to incorporate very sophisticated instrumentation and metrology into the design [4].

In the same period the standards governing product design and manufacturing have undergone basic international harmonisation.

Focal points of interest included; workpiece microgeometry [5] and geometrical deviations [6], as well as tolerancing principles such as; Independency principle, Duality principle, Functional control principle, Feature principle, General specification principle, Rigid workpiece principle, Responsibility principle according to in-ternational GPS Standard [7], which applies to the interpretation of GPS indications on all types of drawings.

In many countries, the above-mentioned international standards have been adopted also on a national level, similar as the new international standards about quality assurance, quality management and environmental management [8, 9, 10].

In this respect the general term "Geometrical Product Specifications and Verification – GPS" has become recently well-known for the area of mechanical engineering. It defines on a technical drawing the shape (geometry), dimensions and surface characteristics of the workpiece under discussion. In this way the optimal function of the respective part is supposed to be guaranteed considering certain manufacturing tolerances. Nevertheless workpieces will be produced, which do not fulfill these requirements. Therefore workpieces are measured in order to compare them with the specifications. There is a need to relate between actual workpieces and:

- the workpiece imagined by the designer,
- the workpiece as manufactured,
- the knowledge about the workpiece as measured.

In order to establish this relationship between design, production and measurement and to clarify the mutual importance, standards have been developed in the area of GPS. Comprehensive knowledge in this area is an important presupposition to achieve economic design, construction, production, metrology and quality management. The concept of the GPS includes:

– several types of standards, some are dealing with the fundamental rules of specification, some are dealing with global principles and definitions and some of them are dealing directly with the geometric characteristics;
– different geometric characteristics such as size, distance, angle, form, location, orientation, roughness;
– workpiece characteristics as results of different manufacturing processes and the characteristics of specific machine elements

and

- occurs at several steps of the product life cycle, in the development of a product, design, manufacturing, metrology, quality assurance, etc.

This concept is represented in Figure 2, showing four different group of GPS standards and designated as the "GPS-matrix-model" (Figure 2) [14].

3. Precision Metrology in Modern Production Environment

An important development as far as workpiece metrology is concerned is the big general advance of coordinate metrology which also happened in the same period of time as computer-aided metrology and "GPS" in general.

Three dimensional coordinate measuring machines (3D-CMMs) allow to measure deviations of dimensions, form and position very accurately with only one measuring device [15]. Besides measuring accuracy the number of workpieces to be measured is important when choosing the measuring device. Especially when workpiece tolerances are more accurate than tolerance grade IT5 (e.g. 11 μm for 50 mm) it is necessary to make use of coordinate metrology. This is also possible for big series of workpieces.

CMMs are referred to as those measuring instruments giving physical representations of a three dimensional rectilinear Cartesian coordinate system.

– The nature of coordinate metrology can be defined as:
– The geometrical features of the workpiece to be measured are touched in several measuring points using a coordinate measuring device.
– The coordinates of the measuring points are used to compute the mathematical geometry of the workpiece with help of the control computer of the CMM.

At the time being coordinate metrology is a very important tool to solve problems of production metrology of nearly any kind especially when high flexibility and high accuracy are demanded at same type of workpiece. One of the essential requirements in coordinate metrology is the computation of associated features from the

The Fundamental GPS Standards	The Global GPS standards	
	General GPS Matrix General GPS chains of standards	
	The Size chain of standards The Distance chain of standards The Radius chain of standards The Angle chain of standards The Form of a line The Form of a surface The Orientation chain of standards The Location chain of standards	The Circular run-out chain of standards The Total run-out chain of standards The Datum chain of standards The Roughness chain of standards The Waviness profile chain of standards The Primary profile chain of standards The Surface defects chain of standards The Edges chain of standards
	Complementary GPS Matrix Complementary GPS chains of standards Process specific tolerance standards Machine element geometry standards	

Fig. 2. The GPS-matrix-model – GPS Masterplan – Overview

probed contact points.

Besides coordinate metrology modern optoelectronic methods are important measurement tools in computer integrated production plants and also as basic tools for global quality management and quality assurance activities. Their efficient use and correct calibration are crucial requirements for quality management in this environment.

Presently exists the general development from micro technology to Nanotechnology. Nano technology describes new innovative manufacturing technologies, finishes, tolerances and especially measurement technique in the nanometer range [11] which especially is called Nanometrology.

In pursuance of this aim since about 1982 new high resolution and high precision measuring devices have been developed, especially Scanning Tunneling Microscopy (STM) and Atomic Force or Scanning Probe Microscopy [12, 13]. For highest demands these methods make it possible to explore miniature structures and in general very accurate and small industrially produced parts and structures. With these measuring instruments lateral resolutions up to 1 nm are achieved and in perpendicular direction it is possible to achieve atomic resolution. Actual developments give evidence that in the near future it will be possible that such instruments will be used in high level industrial quality control laboratories especially also in advanced SMEs. Figure 3 shows the measurement data of the surface structure of a workpiece surface after precision machining.

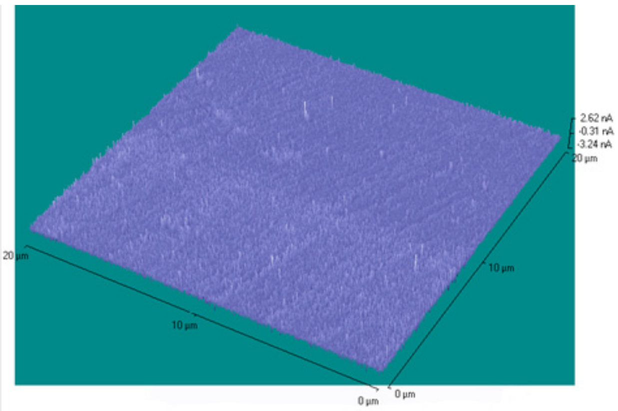

Fig.3. High accuracy 3D topography measurement using the AFM after surface finishing

4. Workpiece Quality in the Context of GPS

In general it is the intention of the manufacturer to satisfy all requirements that are demanded for a product. Every manufacturer is looking forward to satisfy all the criteria that its product must have. Technical means, tools and methods are used to ensure the consistency of product characteristics. One of its important characteristic or feature is geometrical specification or it is better to say Geometrical Product Specifications (GPS). Geometrical Product Specifications are a means to transform function dependent demands into produced workpieces and parts based on:

– mathematical rules and methods,
– consideration of macro and micro geometry,
– possibilities for measuring of quantities and especially toleranced quantities and
– evaluation of uncertainty, etc.

Generally there are many definitions and concepts in Geometrical Product Specifications and Verification (GPS) but one of them which has been presented some years ago named "Skin-Model" [15] was studied in the frame of some research projects. The "Skin-Model" presents a new description for Geometrical Product Specifications and Verification (GPS) with its associated details and on its basis every workpiece can be geometrically defined and considered by applying manipulations of the workpiece geometry. This determination is based on mathematical rules and definitions. It means that according to this determination every workpiece can be designed and on the other hand according to the design it can be measured very clearly [16].

The Skin-Model is based on some general and basic definitions and it uses some tools which are named "Operations" which can be compared with mathematical operations as in mathematics and especially in arithmetic (Figure 4).

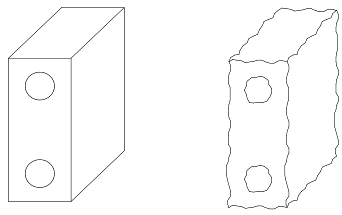

Fig. 4. Ideal model and "Skin-Model" of a workpiece

By application of appropriate evaluation software the measuring results can be transformed into suitable data format that can be used for further calculation and study. In the next step the measuring results will be evaluated with applying computer programs, which are available for statistical evaluations. Now the quality control department will be able to analyse this phase easily and can give necessary advice or notice to relevant other departments especially in the developing and planning domain.

This gives principal ideas in respect of the evaluation of measurement results with regard to GPS.

5. Conclusion and Outlook to Future Developments

The ideas presented in this publication explain in principal the correlation between different geometrical deviations and the manufacturing conditions. This can help to achieve lower manufacturing costs and at the same time higher quality, accuracy and efficiency in present production.

At the atomic level metrology and fabrication are closely related. 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 operate autonomously in the micro- or even nanoworld. The speed and reliability that can be achieved make any idea of mass manufacturing, now, or in the foreseeable future, preposterous. But in any case nanometrology has become technical reality and pico- and femtometrology will not be impossible in the future.

The results of the presented study can be seen as a further step in the direction of a comprehensive analysis of workpiece geometry and it is fully in line with research work already carried out in the past [17]. By the described successful application of intelligent tolerancing and metrology for the solution of measurement problems of various kinds also new challenges are put onto precision production measurement technology especially in the area of GPS.

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