14. Measuring and Quality Control

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Considering the incessantly increasing requirements on the quality of products and processes, it is necessary to ensure a quality-orientated management in all departments of any type of company and the advantageous application of manufacturing measurement equipment.

In addition to diverse technical requirements, the requirements of national, international, and company-specific norms must also be considered. Companies must not only fulfill the requirements of quality but also those pertaining to safety, the environment, and the economy.

In the following, some aspects of manufacturing measurement technology and quality management and their integration into a manufacturing process will be introduced.

Starting with manufacturing geometrical conditions and statements on drawings (nominal state and geometrical limits) the use of measurement equipment and gages to the evaluation of geometric elements will be described. Basic knowledge of measurement standards, measurement uncertainties as well as calibration and testing of measuring instruments are presented. Based on the physical principles, the equipment and methods for the registration of measurement values, form and position deviations, and surface characteristics will be introduced.

14.1 Quality Management

Nowadays, the quality of products, assemblies, and services not only includes the fulfilment of functional requirements by maintaining tolerances. It also includes the fulfilment of numerous requirements such as shown in part in Fig. 14.1. In this section, some fundamentals of quality management will be described from the multitude of requirements. In Sect. 14.2, some aspects of the requirements of manufacturing measurement technology for the qualification of the geometrical quality of products will be shown.

Among the requirements for organizations involved in quality control, the key concepts of quality management (QM) and total quality management (TQM) include planning, monitoring, and improvement of quality, such as the consideration of representatives and departments relevant to quality, as shown in Fig. 14.2.

14.1.1 Quality Management Methods

To conform to the requirements of modern quality management, nowadays numerous procedures and methods, with many different applications, are available [14.1]. Figure 14.3 presents a selection of relevant methods used in the area of mechanical engineering.

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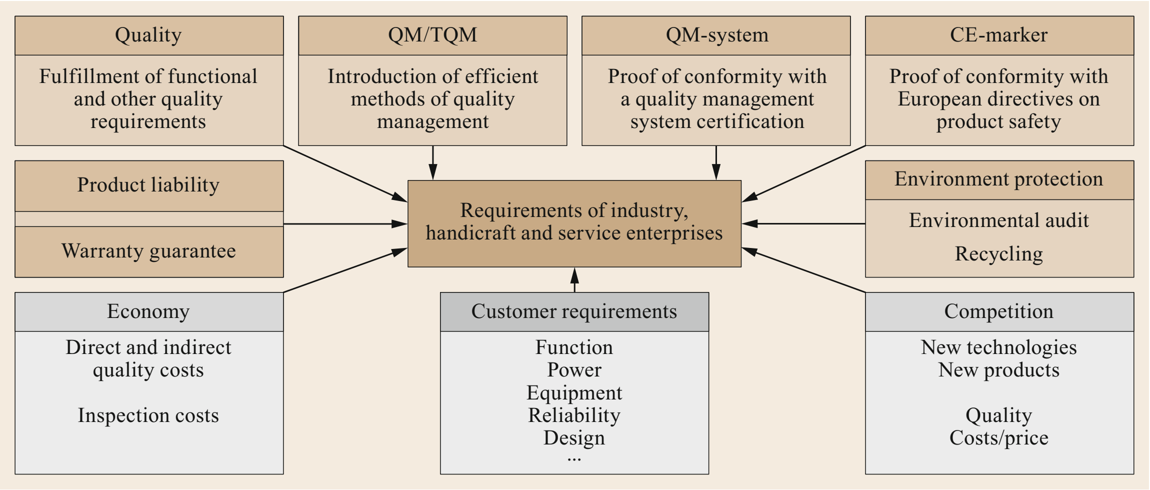


Fig. 14.1 Requirements for industry, craft, and service enterprises

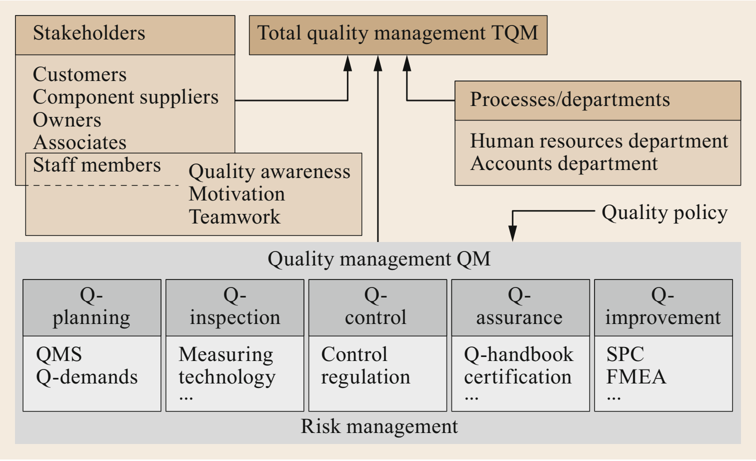


Fig. 14.2 Elements of quality management

The different methods can be associated to two essential groups: *problem-resolving techniques* and *preventive techniques*. The problem-resolving techniques can also be divided into the two other categories: those that find causes of existing quality problems and those that help the engineer develop definite aims in a systematical manner (management methods).

The prime conditions for quality analysis are the collection and preparation of quality data with respect to measured data. *Tally lists* enable a visualization of the accumulation of certain failures or various kinds of mistakes. *Histograms* demonstrate the probability of the occurrence of a certain event within intervals of the measurement range. *Pareto analyses*, also called *ABC analyses*, enable a weighting of the dominant influencing parameters. In combination with the corresponding costs, they are known as Lorenz–Pareto analyses.

Referring to a definite problem, a comprehensive structuring of clustered influences or causes can be presented as a *cause–effect diagram*, also known as a *fishbone diagram* or *Ishikawa diagram*, which can be used to solve possible problems.

The determination of pairs of values in an x–y coordinate system is especially applicable in the experimental causal research of measurement (e.g., quality characteristics). These *scatter diagrams* can be described with the help of statistical calculations, such as regression and correlation analyses, in which the identified regression function describes the kind of functional connection, while the correlation describes the intensity of that connection through the correlation coefficient.

Nowadays, *analysis and evaluation of the quality capability* of procedures and processes takes place

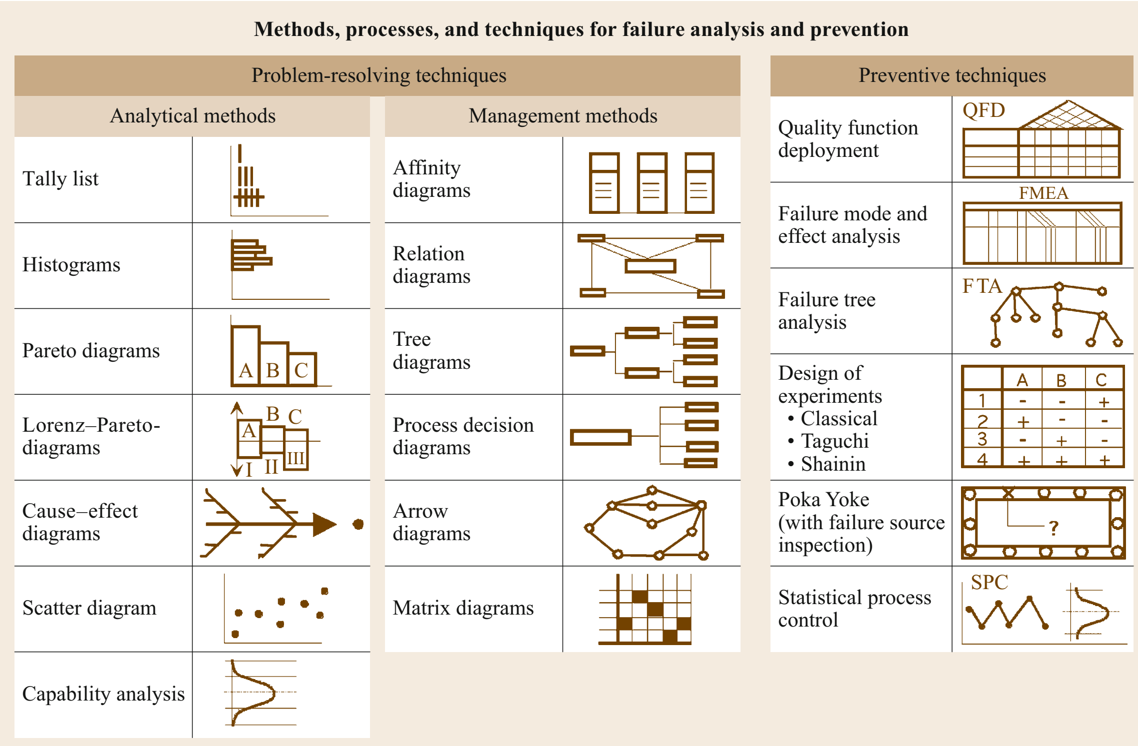


Fig. 14.3 Problem-resolving and preventive techniques

in many areas of mechanical engineering by a comprehensive statistical evaluation in terms of capability coefficients, which express the relation of process spread (6σ) to the tolerance and the position of the arithmetic mean of the tolerance borders. This way, it is possible to compare the quality level of different processes.

Management methods support the solution of problems by a targeted systematic procedure. *Affinity diagrams* allow a structured systematization of ideas in order to point out the correlation between these ideas.

Relation diagrams enable the development of cause–effect relations by visualizing networked structures. *Tree diagrams* specifically subdivide aims until directly realizable activities are practicable.

Firstly, *process–decision diagrams* start by arranging possible problems by

- Urgency
- Probability of occurrence
- Difficulty of prevention.

With the aim of detecting potential problems already in the planning phase and to elaborate corresponding countermeasures.

Arrow diagrams or *net plans* are important resources for project planning for the investigation of *critical paths*, which determine the total permanence of a project. In this method, the determination of a process sequence is made using series and parallel paths to develop a detailed explanation of the working steps required to achieve the project aim, followed by the assignment of the corresponding process durations.

If a lot of information quantities for certain circumstances are available, *matrix diagrams* are suitable for detection of latent structures. By using data evaluation in pairs with the help of matrices for different characteristics, this method enables, for instance, manufacturing and market analysis.

Nowadays, in the field of preventive techniques for failure prevention in technological processes, the schematically compounded methods shown in Fig. 14.3 are mostly applied.

In current quality management, product-related customer wishes are the source of motivation for development from the designing process through the manufacturing process up to the delivery of the products.

With the help of *quality function deployment (QFD)* the *voice of the company* can be developed from the *voice of the customers*. The QFD method systematizes this process under the application of matrices based on the following four steps:

- Customer wishes in terms of product characteristics
- Product characteristics in terms of part characteristics
- Part characteristics in terms of manufacturing regulations
- Manufacturing regulations in terms of production instructions.

Every phase can be described by matrices in the form of a so-called *house of quality*.

This method offers the possibility of affecting the production aim in the conception phase and at the same time obtaining information about the critical product and process characteristics for the fulfilment of customer expectations. Besides the implementation of marketing information in the product, target conflicts between the individual product characteristics may also become visible.

For the detection of potential failure modes during product development, the introduction of new manufacturing methods and the modification of manufacturing technologies' *failure mode and effect analysis* (FMEA) is used. FMEA is especially used in the case of cost-intensive and risk-products and processes. FMEA has universal application and is not connected with a special field. At the base of a standardized procedure, which can be supported by corresponding blank forms, the main steps of a FMEA can be divided into risk analysis, risk assessment, the determination of measures, and the evaluation of effectiveness. The risk evaluation results from evaluation of the probability of occurrence, its importance (for the customer), and the probability of detection of the corresponding failure before delivery to the customer. The advantages of FMEA are above all a decreased number of failures in the early phases of product manufacturing and in product planning.

The systematic search for imaginable reasons for a failure, called an unwanted event, is possible with the method of *failure-tree analysis*. This method, which originated in the field of safety engineering, enables an evaluation of fixed correlations by the determination of the quantitative probability of the appearance of failures.

For this purpose, the function of single components (devices) is described under different conditions using a so-called *components tree*. A subsequent system analysis aims to holistically describe their organization and the behavior of the technical system. The contribution of the individual components to the protection of the overall function of the system, the evaluation of the consequences of the environmental influences of the overall system, and the description of the reaction of the overall system to failures within the system, of resources and by faulty operations, can be described by a failure-tree analysis and calculated or simulated by various evaluation methods.

The methods of *statistical research planning* have the general aim of adjusting the relevant product and process parameters using a systematically procedure in such a way that the quality-relevant characteristics closely approach the ideal value with as few experiments as possible.

The weighting of the influencing factors and the quantification of their effect can be achieved based on classical statistical research planning using mathematical models (such as factorial research plans); if there are a very large number of influencing factors, this can be solved with the help of the empirical procedures developed by Taguchi or Shainin.

The *Poka Yoke* method (from the Japanese: the avoidance of unintentional errors) is dedicated to preventive avoidance of failures in manual manufacturing and assembling processes through the development of precautions (design measures that eliminate incorrect handling) and facilities for failure avoidance for immediate failure detection in the manufacturing process. This can be realized by a comprehensive implementation of applicable rules for product and process design or by the use of simple ancillary equipment.

The *statistical evaluation and control of the quality of processes* (statistical process control (SPC)) is not only a main goal of modern quality management systems but is also required for cost-efficient production processes.

The aim of the use of statistical methods in quality management also exists in the classical detection of faulty products in the manufacturing process and is increasingly widespread in the qualitative monitoring, control, and improvement of the manufacturing and assembling process.

According to algorithms such as that shown in Fig. 14.4 some basic decisions can be made.

Quality control of processes can be performed using continuous, 100% inspection or on the basis of periodically chosen samples in the form of statistical process control (SPC). Statistical methods can also be used to achieve the aim of monitoring and improving product and process quality. Therefore, it is a direct component

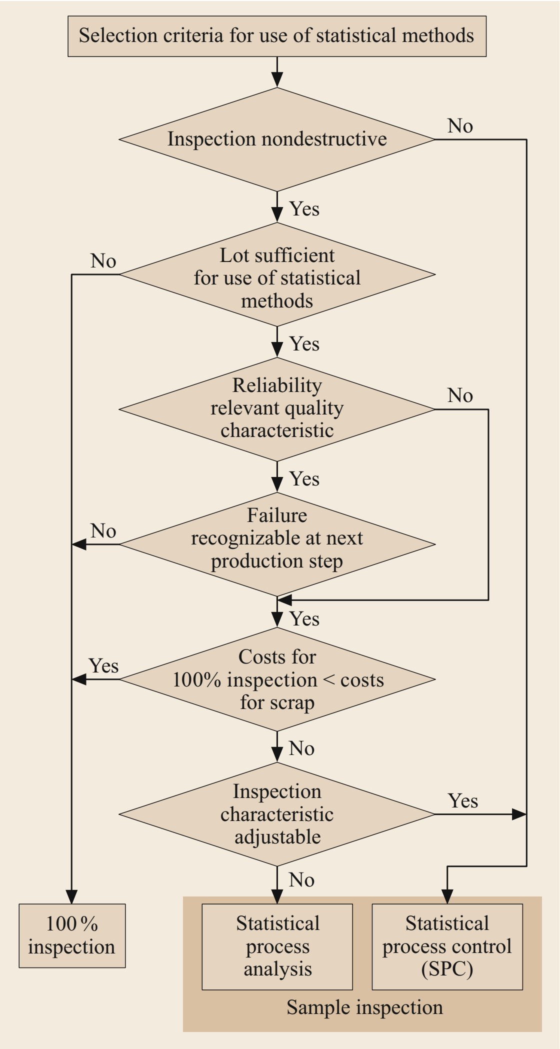


Fig. 14.4 Selection criteria for the use of statistical methods

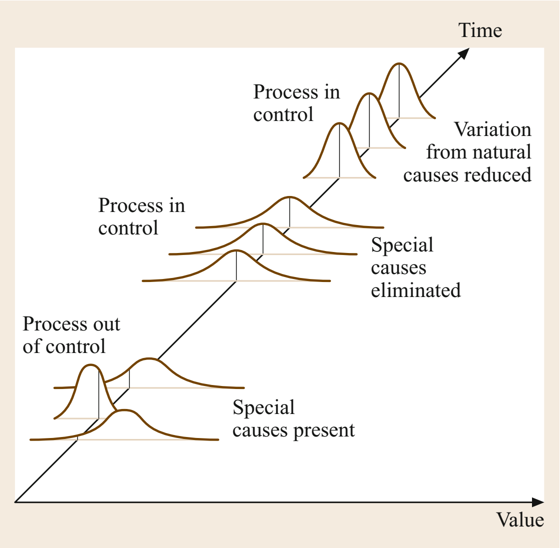


Fig. 14.5 Overview of the use of statistical methods for the evaluation and control of processes

of the quality control circle. The most important methods in this regard are (Fig. 14.5):

- Measuring controls with statistical control algorithms
- quality control charts
- Capability analyses and evaluations
- Sample inspection by statistical sample plans.

Processes in practice, especially newly-introduced processes, are influenced by numerous systematic and random influences, which make the use of statistical methods difficult.

Many statistical methods require the prerequisite of a normal distribution (e.g., double-sided tolerances or limited quality characteristics) or a logarithmic normal distribution (e.g., one-sided tolerance quality characteristics), which are free of systematical influences.

In such cases, we also speak about the requirement of stable or stationary processes or of so-called *processes in or under statistical control* (Fig. 14.6).

If stable processes are available, they can be further inspected using quality control charts. A quality control chart (QCC) is a graphical representation of a process calculated from the measured results from a small sample or chronological characteristics. The target of quality control charts is to capture quantitative changes in a process that exceed statistically derived control limits (Fig. 14.7).

The recorded results can then be the basis for subsequent statistical evaluations or characterizations in the form of capability coefficients. These coefficients can also be used for the evaluation of machines and processes.

If a product-orientated decision about the acceptance or rejection of a product series or lot takes place, sample plans can be used. The producer (supplier) may also use these in the form of a final inspection, as may the customer in the form of an inspection on receipt.

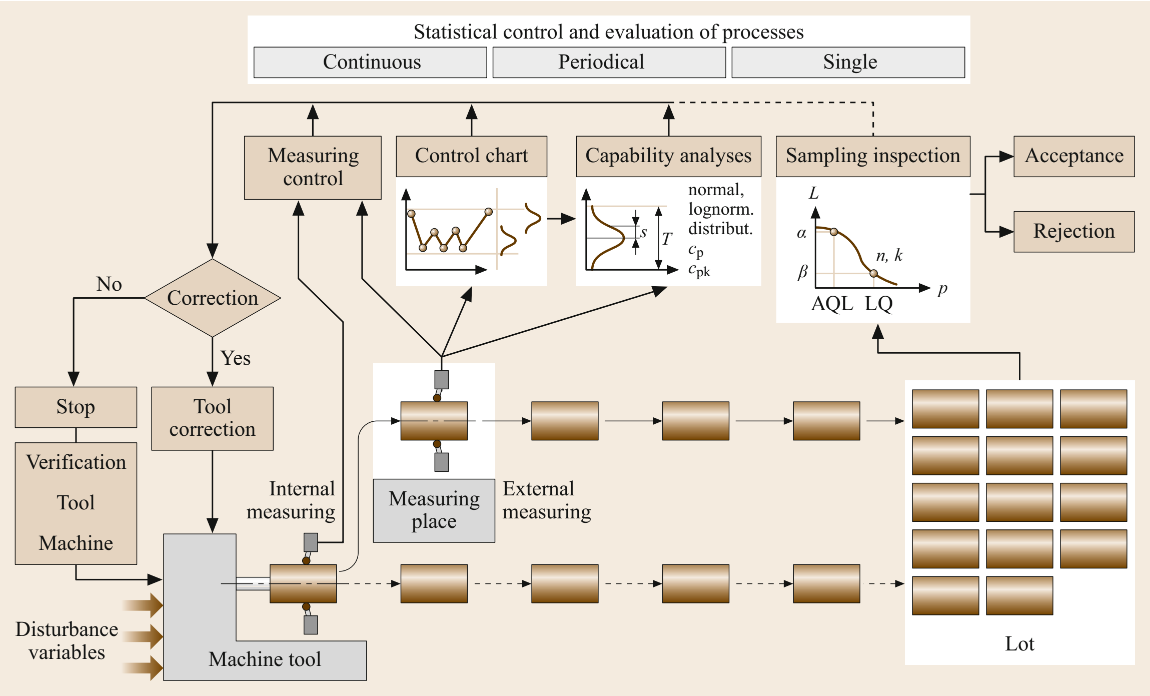


Fig. 14.6 Stabilization of processes through the reduction of systematic and random processes disturbing variables

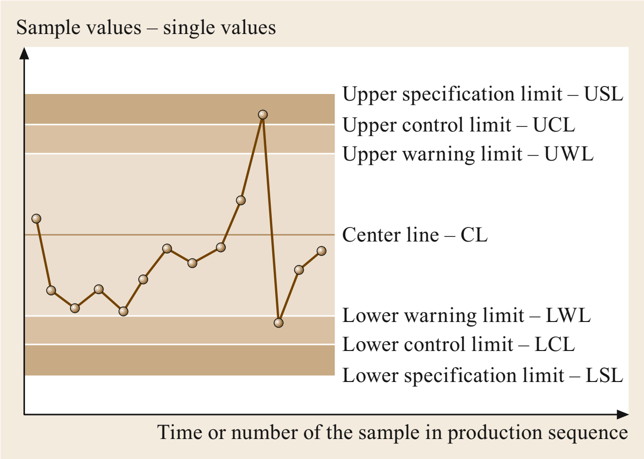


Fig. 14.7 Process monitoring with quality control charts

Statistical analysis results have a wide variety of uses in quality monitoring, evaluation, control, and management, as is shown in Fig. 14.8.

14.1.2 Quality Management Systems

The organizational realization of the concept of quality in all departments of enterprise and in all phases of product realization can be supported by *quality management systems* (QMS), as is shown in Fig. 14.1. In addition to this, the organizational structure and the processes organization of all quality-relevant departments and operations can be evaluated and compared to standardized regulations. The successful introduction and realization of a QMS can be evaluated and validated by an accredited certification body.

As the basis for this, the independent ISO 9000 series of standards can be used [14.2–5]. Based on this, for the worldwide automotive industry, comprehensive additional requirements exist, which are fixed in company-dependent standards. Efforts for the integration of the different requirements of the automotive industry to date are contained in the standard IATF 16949 [14.6].

14.1.3 CE Marking

Within the single market of the European Union, a requirement for the commencement of operation and the placing on the market of products is the fulfilment of harmonized safety requirements. To obtain a conformity certificate for these European Community (EC) requirements, a CE marking is required. This is also valid for products that are produced outside of the European Union if they are also distributed within it.

Examples of EC directives include those for machines, toys, electromagnetic compatibility (EMC), detonating devices, and medical products, etc.

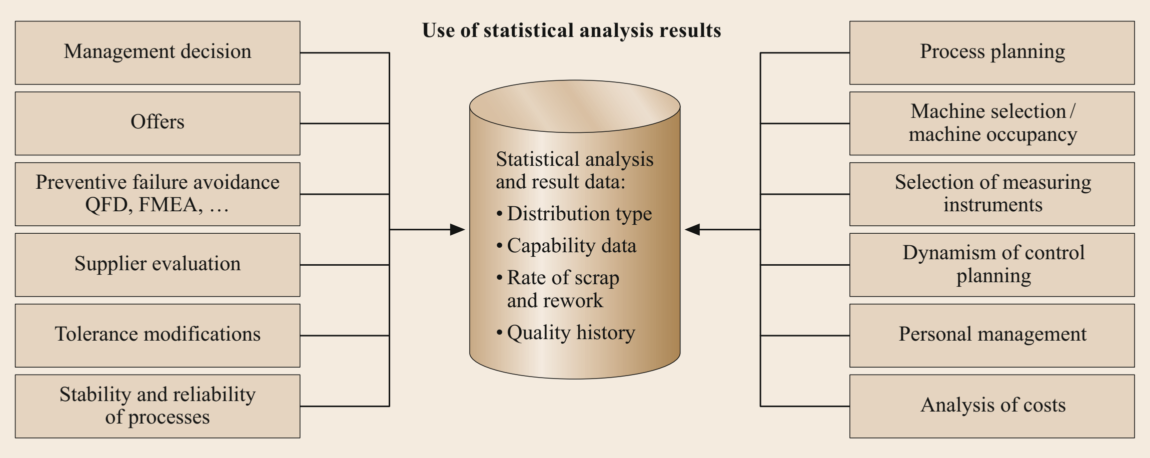


Fig. 14.8 Use of statistical results

14.2 Manufacturing Measurement Technology

Measurement is the determination of the value of a physical quantity (measured quantity) by comparison with a reference value.

Manufacturing measurement technology is part of the field of measurement technology. It deals with the methods, equipment, and strategies for measurement in the realm of mechanical production processes. Manufacturing measurement technology is utilized in various locations, such as rooms with special, controlled environmental conditions, as well as directly integrated into the assembly line. The aims of manufacturing measurement technology are:

- Evaluation of the product
- Evaluation of processes and machines
- Quality-orientated process control.

Here we confine the discussion to the description of the relevant geometrical features and/or technical aspects of obtaining such objects from workpieces. These features include lengths, angles, distances, and surface structures. Most of the principles and definitions described also apply to nongeometrical parameters. The relevant SI unit used to describe these geometrical features is meter. Angles are described in degrees or radians.

The physical measurement that comes from the measuring process is called the measure. The object from which this quantity was measured is called the measuring object. The value of the measure, which actually exists but is currently unknown, is the true value. The aim of the measuring process is to determine this true value. A variable that does not change with time (for example, a diameter) is measured by a static measurement. Dynamic measurement is the measuring of a variable that changes with time (for example, a vibration) or the measurement of a variable, whose variation arises from the time-dependent behavior of another variable (for example, for a roughness measurement, the dependence of the measured value on the scanned measuring length).

In order to determine whether an object fulfils a particular requirement, it is inspected. As subjective inspection should not be considered, one can differentiate objective inspection into measuring and gauging. The inspection means that are employed can be divided into indicating measuring devices, measurement standards, gauges, and additional measuring devices. Figure 14.9 shows a digital dial indicator and a measuring block, as the most important measurement standard of dimensional measuring technology. Measuring blocks are quadrilateral metal or ceramic gauges, whose parallel end faces have a known width and minimal deviation. A gauge and a stand, an example of additional measuring equipment, are represented on the figure too.

14.2.1 Arrangement in the Manufacturing Process

Measuring technology has become an essential ingredient in manufacturing processes. Figure 14.10 shows the multitude of integration possibilities and the corresponding relationships between the production process and measuring technology as well as different possibilities for analyzing the measured data and its feedback into the process.

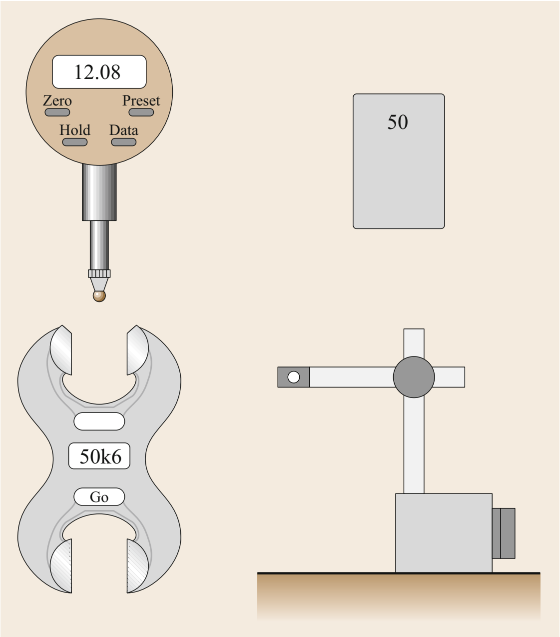


Fig. 14.9 Inspection devices

Inside every tooling machine integrated measuring devices are used to collect parameters (the position of the axes, temperature, force, voltage, current, etc.). These values can be directly used by the machine operator or the machine itself to control future operations. In reference to the collection of data from finished products and in consideration of the drawing specifications, these finished product parameters can be evaluated, classified, and documented. Furthermore, parameters can be derived from the measured values through continued analysis, or more specifically, these parameters that can regulate or control the machining or production of the product. Using an adjustment, the measured value (the controlled variable), which has an instantaneous value, is continuously measured and corrected with a controller with respect to a known value (the set value). It is then possible to eliminate disturbance factors from outside the process. The constant, targeted influencing of a process on the basis of a previously defined model without feedback is what is meant by open-loop control.

Starting from the process analysis, the machining process and/or the processing machines themselves can be evaluated (for example, for machine and process capabilities) and documented. The result of the machine evaluation is, for example, a quality-orientated machine selection. Should the machine not be in a position to produce the desired tolerances, selective inspection and correction of the machine systems may be necessary, or a complete overhaul or a new revision of the machine may even be necessary. Through the additional use of measuring technology for preventive monitoring of a machine, it is possible to implement maintenance procedures or schedules to avoid losses or stops in production.

14.2.2 Specifications on the Drawing

The drawing is the defined input to the manufacturing process based on the required functions outlined by the designer, and is, therefore, the basis for the manufacturing measuring process. The complete, integrated product drawings, as well as single-product element drawings, are used to clarify the permitted allowances and, thereby, the tolerances for manufacturing. The geometrical specifications can be separated into measuring

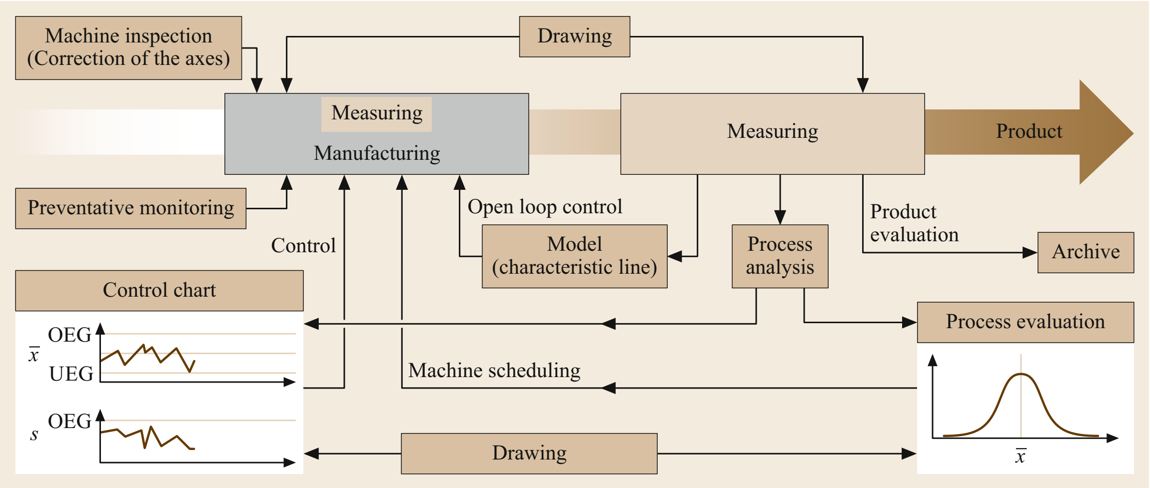


Fig. 14.10 Measuring technology and measuring value analysis in manufacturing processes

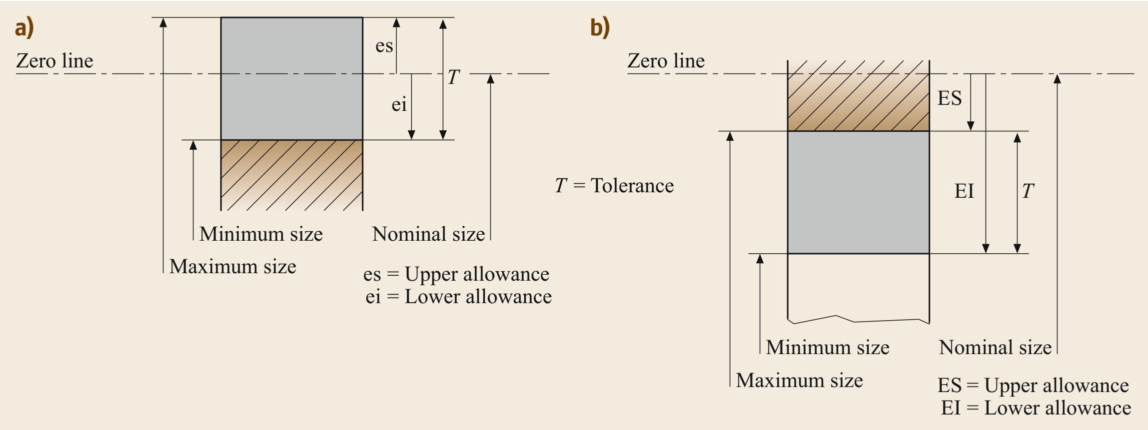


Fig. 14.11a,b Tolerance specifications for lengths: **(a)** shaft, **(b)** hole

tolerances and shape tolerances. Shape tolerances include not only form and position tolerances, but also surface finish tolerances, which can be divided into roughness and waviness.

Tolerance specifications for lengths consist of the nominal size and defined permissible upper and lower allowances (Fig. 14.11). The nominal size plus the upper allowance is the largest acceptable measure, and the nominal size plus the lower allowance is the smallest acceptable measure. The difference between the upper and lower allowances is the tolerance. The definition on the drawing is shown through the specification of a nominal size supplemented either directly by a coded specification of the allowance or through a letter and a number combination (ISO 286 [14.7, 8]). The letter describes the position of the tolerance field with respect to the zero line, and the number represents the magnitude of the tolerance. The specification $36^{-0.025}_{-0.050}$ corresponds to the drawing specification, 36f7, which, in manufacturing terms, means that the largest acceptable measurement is 35.975 mm, and the smallest acceptable measurement is 35.950 mm. Whenever the nominal sizes are the only values displayed on the drawing, free size tolerances according to ISO 2768 can be specified [14.9, 10].

The position of the tolerance with respect to the zero line (which corresponds to the nominal size) and the size of the tolerance determine the function of the proposed piece. The size of the tolerance is, furthermore, decisive for the cost of the manufacturing process.

The form and location tolerances in each case define zones, into which the corresponding element must fit in, when it is within the tolerance. Form tolerances, which are defined in ISO 1101 [14.11], are shown in Table 14.1. Single elements, such as lines, rectangles, circles, cylinders, and profiles are specified as form tolerances. Position tolerances are divided into direction,

Table 14.1 Form tolerances

Form tolerances	Single elements
Straightness	—
Flatness	▱
Roundness	○
Cylindricity	⌭
Profile	⌒

Table 14.2 Position tolerances

Position tolerances		Related elements
Direction	Parallelism	//
	Perpendicularity	⊥
	Angle	∠
Place	Alignment	⌖
	Concentricity	◎
	Symmetry	⌯
Run	Runout	↗
	Total runout	⌰

place, and run tolerances, as summarized in Table 14.2. In each case, position tolerances refer to an individual element of the workpiece. On the drawing, the necessary specifications are represented in a tolerance frame (Fig. 14.12). The tolerance frame contains a symbol that describes the type of tolerance that is being signified and a tolerance value, possibly with a reference length. The indication arrow connects the tolerance frame with the associated element, or rather the associated lines of

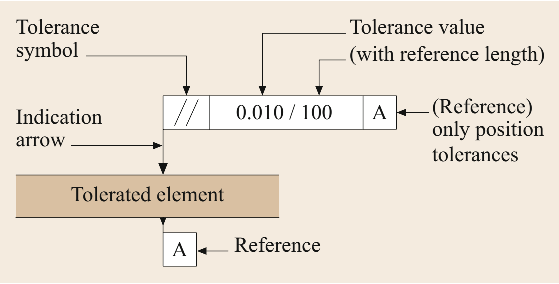


Fig. 14.12 The tolerance frame as a drawing entry

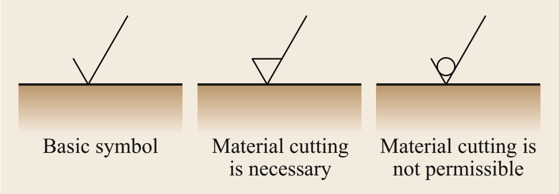


Fig. 14.13 Symbols for surface conditions

measurement or symmetry on the drawing. Whenever the type of tolerance requires it, the reference element is indicated at the end of the tolerance frame through the specification of a letter, which repeats the necessary reference basis. In a few cases, more reference elements are possible.

The tolerance specification for surface finish is shown on the drawing by a basic symbol and supplemented by additional specifications. Whether material cutting machining is *necessary* or *not permissible* is also indicated, as is shown in Fig. 14.13. Additional specifications include tolerances for the roughness value (most of the time, the arithmetic average surface finish (Ra)), and when necessary, amongst others, specifications for the manufacturing process, tolerances for further roughness or waviness parameters, and the grooving direction.

14.2.3 Gauging

Gauges are inspecting devices that represent the dimension and/or form of the workpiece that is to be tested. There are three types of gauges: limit gauges, receiving gauges, and so-called *go and no-go* limit gauges. The procedure is always the same: to try to mate the workpiece elements with the correct gauges. A simple yes or no decision is the result of this process. With limit gauges, one can determine whether the value of a test object is larger or smaller than the value of the gauge (for example, with a pin gauge). With receiving gauges (for example, radius or screw pitch gauges), a comparison is made with the workpiece's form and the form of the gauge, and the best-fitting pieces can then be separated out.

Go and no-go limit gauges are the most important for the inspection of manufacturing tolerance elements. Figure 14.9 shows an example of an external caliper gauge, which is suitable for the inspection of shafts. Limit gauges consist of a *go* side and a *no-go* side, which correspond, respectively, to the largest and smallest measurement possible; the *go* and *no-go* sides are verified one after the other to check for mating. The inspection result is *good* when the workpiece fits comfortably into the *go* side and not into the *no-go* side. The Taylor principle states that, on the *go* side, all the

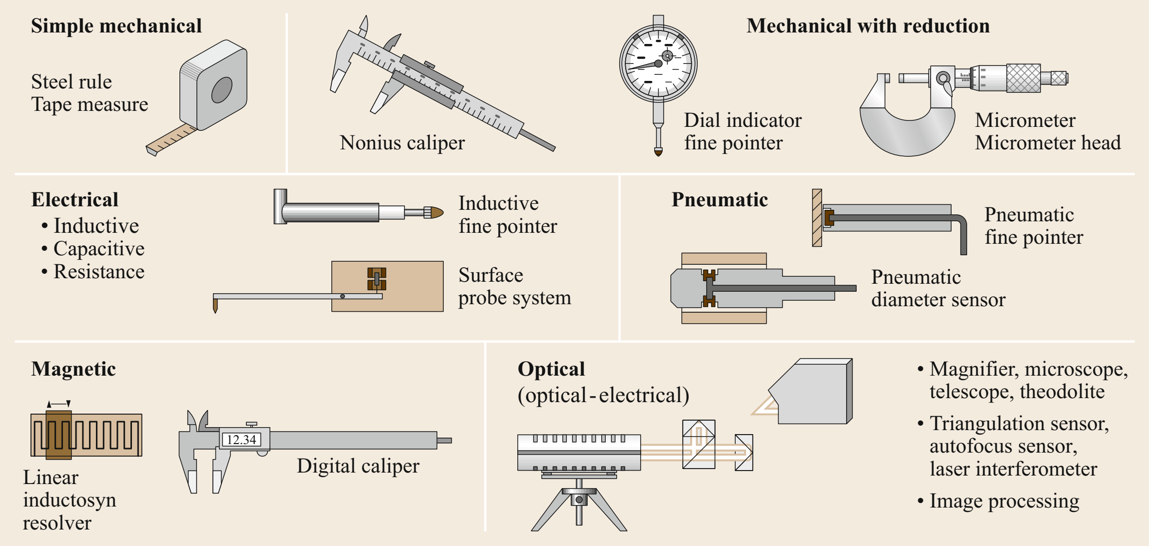


Fig. 14.14 Physical principles of measurement-value collection and example instruments

measurements or control measurements are tested at the same time, but on the *no-go* side, every measurement or control measurement is tested in isolation.

14.2.4 Application of Measuring Devices

Measuring devices work on very different physical principles. Simple mechanical measuring devices include the steel rule or measuring tapes. Measuring devices with mechanical reduction include nonius calipers, dial indicators, and micrometers. Pneumatic systems have long been used because of their noncontact scanning. At present, electrical, magnetic, and optical (more specifically, optical-electrical) principles have emerged in the field of measurements. Their common essential property is that the value measured can be directly transformed into an output signal or onto recording media. A few examples of such equipment are shown in Fig. 14.14.

Essential for a secure measuring value collection is the construction of a measuring chain that is as short as possible and stiff. The measuring chain in Fig. 14.15 is composed of a measuring device, the supports of a stand, a base plate, and the object measured. In the measuring device, starting from the input value (in this case, the displacement of the probe by the measuring object) the output (in this case, the measuring value 8.02 mm) is obtained through the measuring sensor, an amplifier, and an analog-to-digital converter. Depending on which measuring devices are used, their internal parts may be quite different. The output value can then be transferred to a storage device or a processing machine (for example, a personal computer).

The following explains several essential properties of measuring devices. These properties determine the

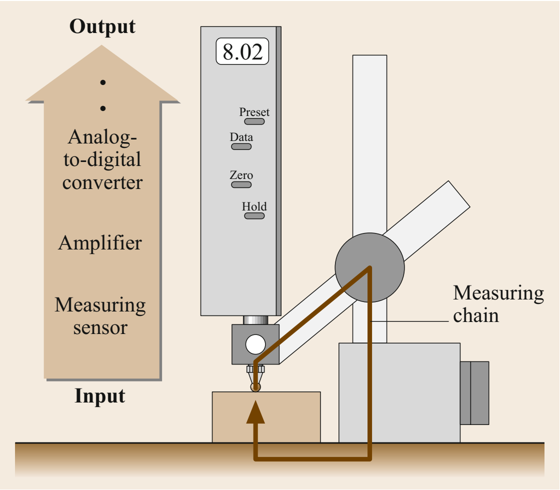


Fig. 14.15 The measuring chain

applicability of the equipment. The achievable *information content* of a measurement is an essential distinction criteria. Also, the *accessibility* of the measuring value to the workpiece reduces the possible selection of measuring devices. The *type of probe* (contact and noncontact) is also relevant. Spheres, planes, or cutting edges are the fundamental probe shapes.

The *indicating range* of a measuring device is the range of values over which the device can indicate (smallest to largest indicated measuring value). The *measuring range* can deviate from the indicating range and corresponds to the section of the indicating range over which the measuring deviations remain within defined boundaries. The *scale division value* is the change in the measuring value that leads to the movement of the pointer from one to the next dash on a line scale (on digit scales to a digit step). When the measuring devices are clamped (for example, by a support, Fig. 14.15), the range of adjustment of the support and the measuring range of the measuring devices constitute the *range of application*. The relationship between the value of the input and the corresponding output value is the *transfer function*. A linear transfer function is usually aimed for. The *threshold limit* is the smallest possible change in the input that leads to a recognizable change in the output. The effect whereby the same value of the input produces two different results depending on the direction in which the value is approached, is called the *hysteresis*. A slow, time-varying change of the output without a change in the input value is called *drift*. The *response time* is the time between a step change of the input and the time when the output value remains constant within a prescribed range.

Additionally, the *measuring uncertainty* should be highlighted as an essential characteristic of measuring devices. A measuring device is qualified for a designated measuring task only when the uncertainty does not exceed a ratio with the tolerance of $U/T = 0.1$–0.2. Because the exact uncertainty of a chosen measuring device is often not known, one can make do with the *limit of error*. The limit of error is the largest measuring deviation of a measuring device and is usually defined for a group of measuring devices through a standard or by the manufacturer.

The *direct collection of measuring values* (for example, with calipers or micrometers) is the easiest type of measuring implementation. The measuring range of the measuring devices must overlap with the measuring object. In Fig. 14.16, the measurement of a length by means of a micrometer is shown. The range of measurement of the displaced micrometer is shown as being 25 mm. Objects with lengths ranging from 0 to 25 mm can be measured. The measuring uncertainty for such a micrometer can be expected to be in the range of 10–20 μm.

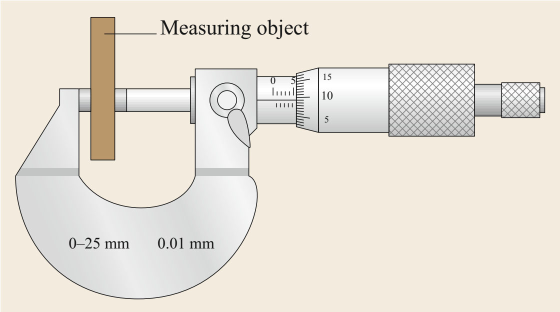


Fig. 14.16 Direct measurement

If the tolerance of the measuring value is so small that the required ratio between the measuring uncertainty and tolerance can no longer be met, one must choose a measuring device with a smaller measuring uncertainty. Smaller measuring uncertainties are often accompanied by smaller measuring ranges. Whenever a measuring device whose range of measurement is smaller than the measuring value must be used, for example because of the requirements of the measuring uncertainty, one can employ *difference measurement* (Fig. 14.17). One chooses a measurement standard, which is shown as a combination of block gauges in Fig. 14.17, whose value differs from the measuring value by no more than the measuring range of the measuring device. The measuring device is used so that the readout both by probing the measurement standard and the measuring object is possible. The length of the measuring object is the sum of the length of the precision gauge block, and the difference between the readout for the measurement standard and the measured object.

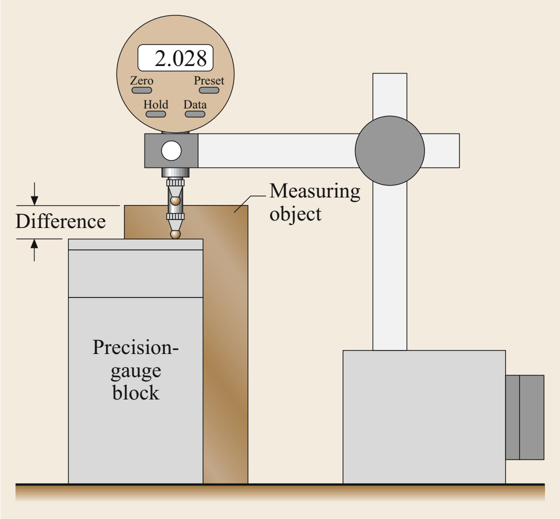


Fig. 14.17 Difference measurement

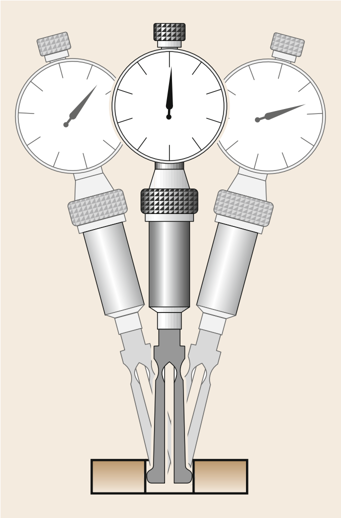


Fig. 14.18 Inversion point

Another important application option is the search for an inversion point. Figure 14.18 shows an example of the measurement of an inside diameter with a two-point measuring instrument (two probing points on the cylinder's interior). Through the measuring force and supported by special structures, the instrument aligns itself so that the cylinder axis intersects the connecting line between the two probe points. The instrument can be pivoted from the left in Fig. 14.18, through the middle, to the right position. One can see that the displayed measuring value becomes smaller at first but, after the middle position, becomes larger. The smallest displayed value, the inversion point of the needle, corresponds to the shortest connection of the probed cylinder surface line and, thus, the diameter.

When measuring workpieces, different influences have a negative impact on the measuring result. For example, inclination between the measuring instrument and measured object, bending, deformation on account of the measuring force, and environmental conditions can lead to deviations of the measurement. Some of these effects can be avoided or notably reduced through the operation of the proper equipment.

Through the adherence to a fundamental measuring technology principle, the Abbe comparator principle, one can reduce the influence of tilting errors. According to this principle, the measured object and the measuring rule are to be aligned flush. Figure 14.19 shows the universal length gauge as one of the essential instruments using this principle. The measured object and the integrated measuring system, which is inside the movable quill, are consecutively aligned flush. Brackets for interior measurement are attached. After removing the brackets the instrument can collect of external measurements. As measuring systems, glass measuring scales

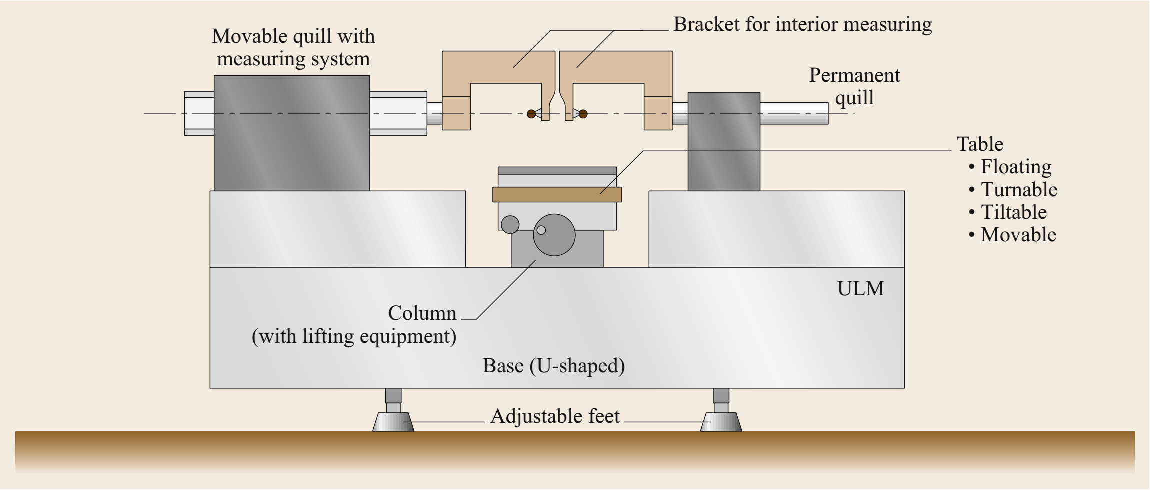


Fig. 14.19 Universal length gauge

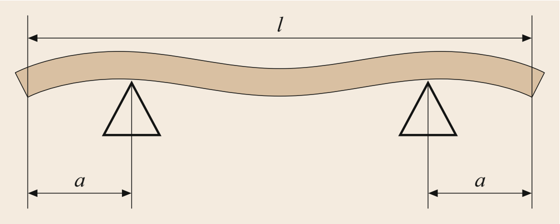


Fig. 14.20 Bessel points

Table 14.3 Linear expansion coefficients

Material	Linear expansion coefficient (μm/(m K))
Steel	13
Copper	16
Aluminum	23
Magnesium	26
Polyvinyl chloride	80

and laser measuring systems are utilized. Such measuring instruments are suitable for the monitoring of gauges and measuring means.

The deflection of workpieces due to their own weight also has a considerable impact on their length. On a bar-type component, one obtains the smallest shortening of the whole length whenever the piece is supported on the so-called Bessel points (Fig. 14.20). These support points are located at a distance $a = 0.220l$ from the ends. Similar effects lead to deformations on account of the measuring force. Deformations of the material are mostly only problematic for soft materials (plastics) and nonmassive workpieces. Here, the workpiece can bend itself whenever the measuring force presses against thin-walled positions. This effect can be reduced using proper fixtures.

Environmental conditions are generally specified by the room where the measurement takes place. Measuring rooms are classified into five classes. Precision measuring rooms (class 1) serve the calibration of reference standards. Fine measuring rooms (class 2) serve for the calibration of the standards used and for acceptance inspection of precision parts. In standard measuring rooms (class 3), measuring tasks for the monitoring of a process, measuring of fixtures and tools, as well as the control of inspection equipment (factory standards) and first prototype inspections are conducted. The production-related measuring room (class 4) serves for monitoring production, machine settings, and instruments. Production-related measuring takes place on the manufacturing measuring site (class 5). The spectrum is supplemented by the special measuring room, for example, for the measuring of semiconductor wafers. Properties whose limit values in every measuring room class are predefined include temperature (basic temperature, time and local temperature variation), vibrations, air quality (fine dust, suspended matter), air humidity, and lighting.

A substantial influential parameter for geometrical data acquisition is temperature. The reference temperature for measurement is 20 °C. The reference temperature is the temperature at which workpieces have their true measurement value and at which the inspection equipment detects it. These specifications apply to all pieces in the measuring chain. Table 14.3 shows the linear expansion coefficients of different materials. For example, for a temperature increase of 1 K, a 1 m-long piece of steel will become about 13 μm longer. The alternative measuring of the existing temperature and consequent correction of the measuring

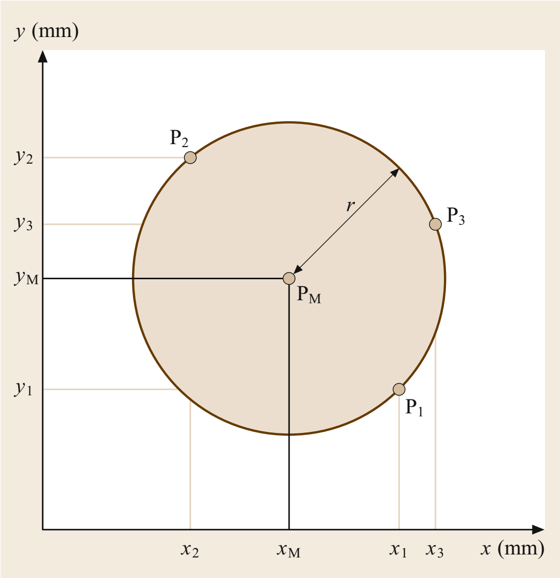


Fig. 14.21 Measuring points on a circle

value is particularly problematic for geometrically and compositionally inhomogeneous inspection equipment or workpieces and with temporally and spatially varying temperatures.

14.2.5 Coordinate Measurements

Coordinate measuring machines are universal, flexibly applicable equipment for the recording of workpiece geometry. As well as measurements of parameter (e.g., diameter and length) position and form (e.g., roundness and concentricity), special (e.g., cylindrical or bevel gears) and free-formed surfaces (castings) can be measured [14.12].

In contrast to conventional measuring techniques, the desired measurements are not measured directly. The principle is the acquisition of single data points from geometrical elements. These elements include circles, planes, cylinders, spheres, and cones. Furthermore, these elements can be combined together to identify distances, angles, or position deviations. The acquired measuring points, which are on the boundary of standard elements, are mostly described by a Cartesian coordinate system (Fig. 14.21, x, y, z). However, it should be noted that cylindrical and spherical coordinate systems are also possible. The described size of these geometrical elements will then be calculated from these measured points. The following example shows the strategy for identifying the radius r and the middle point coordinates x_M, y_M of a circle. For simplification, this example will be confined to a circle in the x–y plane.

The equation for a circle whose center point does not lie at the origin is as follows

$$r^2 = (x - x_M)^2 + (y - y_M)^2 .$$

The variables r, x_M and y_M are unknown. One appoints a measuring point on the circumference of the circle for the variables x and y. Now, because there are three unknowns, and we need a clear description of the circle, we need three equations, which means three data points (the smallest number of data points for determining a circle is three). This yields the following system of equations

$$\begin{aligned}
&\text{For } P_1 \text{ with } [x_1, y_1]\text{: } r^2 = (x_1 - x_M)^2 + (y_1 - y_M)^2 ,\\
&\text{For } P_2 \text{ with } [x_2, y_2]\text{: } r^2 = (x_2 - x_M)^2 + (y_2 - y_M)^2 ,\\
&\text{For } P_3 \text{ with } [x_3, y_3]\text{: } r^2 = (x_3 - x_M)^2 + (y_3 - y_M)^2 .
\end{aligned}$$

Since we are dealing with elements of measured, real-world objects, whose bordering areas deviate from geometrical standards, the collection of a larger number of data points is essential for the determination of the element parameters. An overdetermined (no longer explicitly solvable) system of equations results from a higher number of measured points. This system has the following form

$$\begin{aligned}
&\text{For } P_1 \text{ with } [x_1, y_1]\text{: } f_1 = (x_1 - x_M)^2 + (y_1 - y_M)^2 - r^2 ,\\
&\text{For } P_2 \text{ with } [x_2, y_2]\text{: } f_2 = (x_2 - x_M)^2 + (y_2 - y_M)^2 - r^2 ,\\
&\qquad \vdots\\
&\text{For } P_n \text{ with } [x_n, y_n]\text{: } f_n = (x_n - x_M)^2 + (y_n - y_M)^2 - r^2 ,
\end{aligned}$$

where f_i represents the deviation of the corresponding data point from an ideal circle. One can employ a compensation method to solve this system of equations. A widely used method is the regression equation by Gauss. The sums of the squared deviations are minimized with this method

$$\sum_{i=1}^{n} f_i^2 \to \min .$$

This least-squares method ensures that all measuring points are included in the calculation. Problems especially arise when one wishes to verify mating. In this case, the inscribed circle gives the description for holes, while the circumscribed circle gives the description for shafts. (The *inscribed circle* is the largest possible circle that has all of the measuring points outside, while the *circumscribed circle* is the smallest possible circle that contains all of the measuring points; Fig. 14.22.) In certain cases, an outlier test may be necessary.

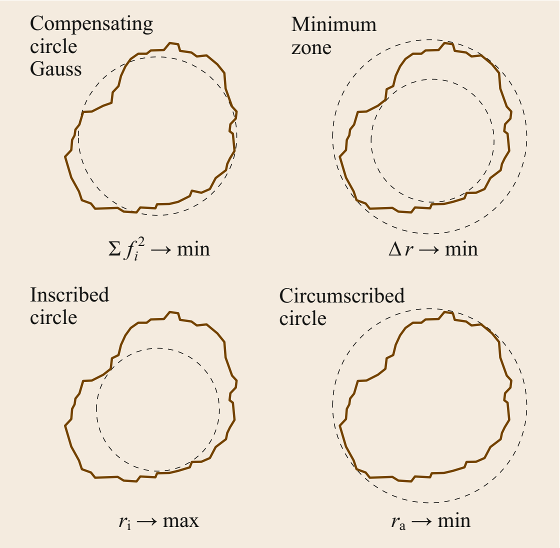


Fig. 14.22 Compensation methods

Equipment, Sensor Technology, and Software

One can subdivide coordinate measuring machines on the basis of their construction into portal, bridge, and standing measuring machines. In Fig. 14.23, the basic configuration of a portal measuring machine is represented. The mechanically embodied axes (in the example shown, portal and quill) are arranged on the measuring table at right angles to each other. Additionally, the axes of rotation can be integrated for the realization of rotary movement. The instantaneous positions of the axes are logged through the measuring system and forwarded to the connected computer. Glass measuring scales are mostly used in measuring systems.

The probe system is attached to the quill. In addition to the frequently utilized mechanical probe systems, there are contactless options such as edge recognition, optical methods, and/or laser probes. One speaks of a multisensor coordinate measuring machine when various probing systems are arranged inside (Fig. 14.24).

Figures 14.25 and 14.26 illustrate various mechanic probing systems. One can distinguish between measuring and switching mechanical probing systems. In both cases, the workpiece is touched with the probe element, which is fixed onto the probing system. The probe element consists mostly of a shaft and an almost ideally round, wear-resistant sphere (in most cases, made of ruby). In a switching measuring system (Fig. 14.25), the contact between the probe sphere and workpiece releases an impulse. At the moment of this signal, the x, y, and z-coordinates of the current position from the table, portal, and pinhole are transferred to the computer and stored there for further processing as required.

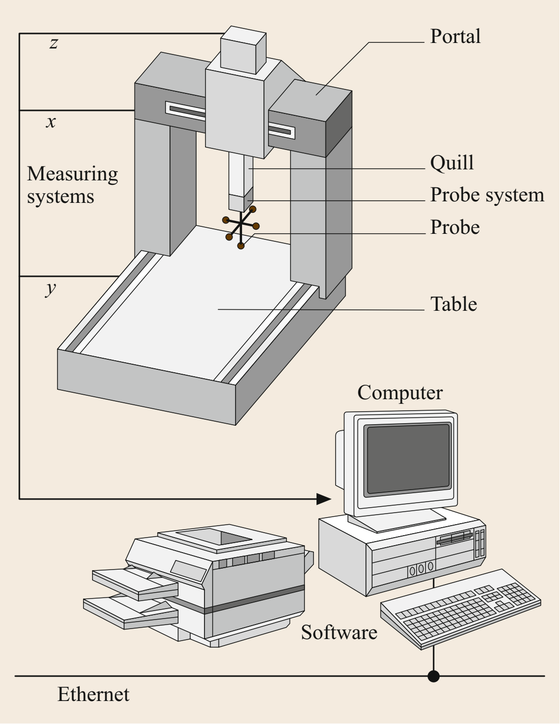


Fig. 14.23 Basic configuration

Contact between the probe and workpiece leads to deflections of the probe head in all three coordinates in a measuring probe system (in Fig. 14.26, the deflection is only represented in one direction). These deflections are measured and combined with the associated coordinates of the inherent positions of the table, portal, and quill. The measuring point coordinates obtained in this way are passed to the computer. However, care must be taken to note that the measuring point coordinates acquired always refer to the middle point of the probe sphere of the reference probe, not to the contact point between actual probe and workpiece.

Very flat outlines or color transitions are not mechanically probable. In these cases, optical acquisition is an option. For this purpose, the measuring object is illuminated, according to the target measurement (using through light, light-field, or dark-field illumination) and imaged through optics. The optics used may work with changed or zoom objectives in order to obtain different magnifications between the measured object and the image. In the simplest case, only the contours to be measured are scanned, using an edge finder. In the next most sophisticated system, based on image processing, the measured object is displayed on a charge-coupled device (CCD) matrix. As with a mechanical measuring probe system, the measuring point coordinates results

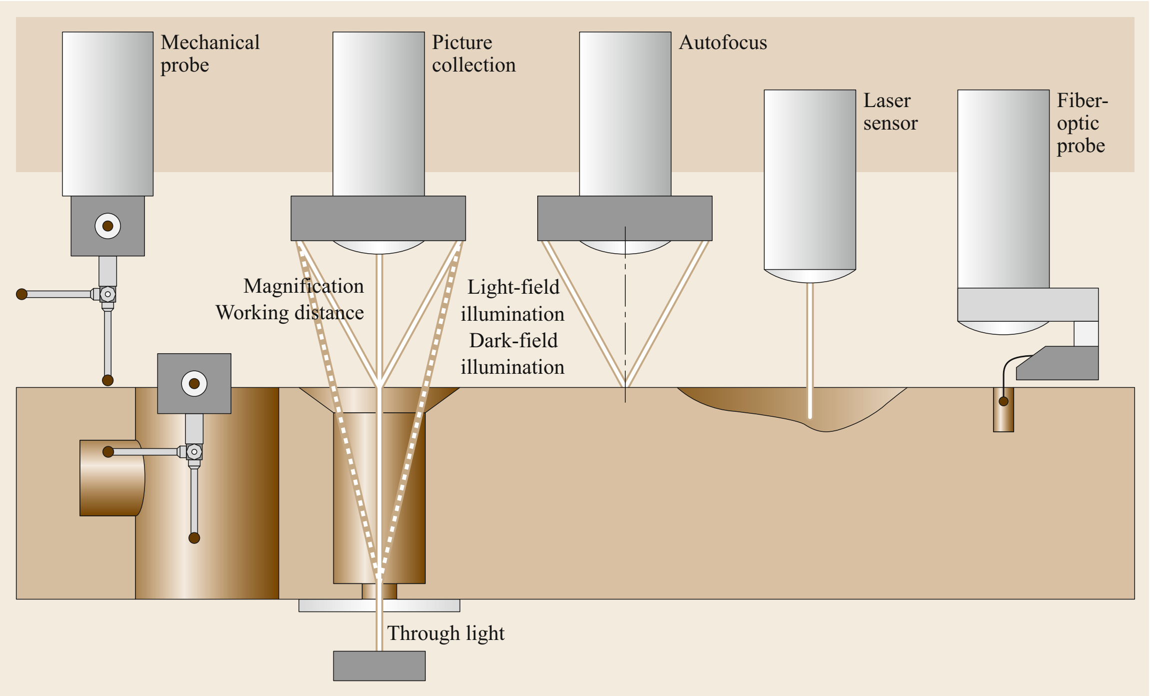


Fig. 14.24 Multisensor technology

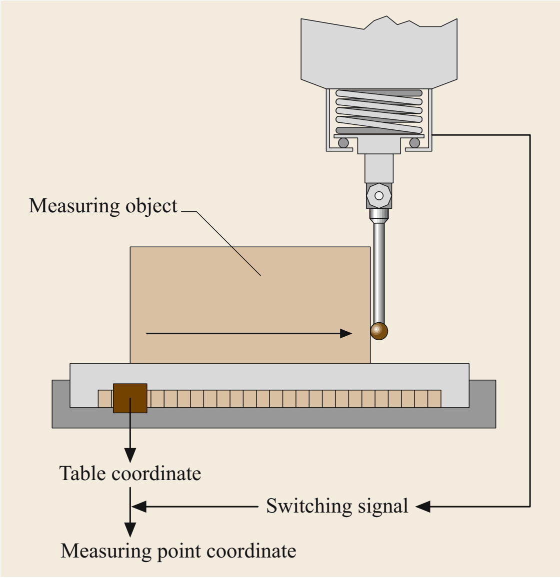


Fig. 14.25 Switching probe system

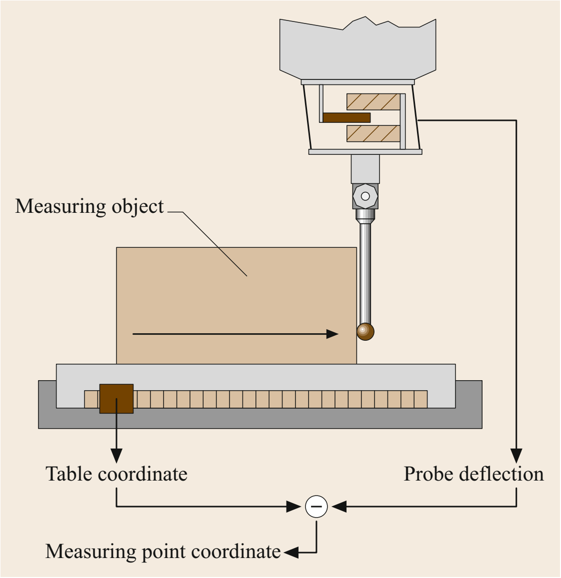


Fig. 14.26 Measuring probe system

as a combination of the pixel coordinates and the inherent positions of the table, portal, and quill.

While the optical variants described so far operate in the x–y plane, the focusing of an optical system can also capture the z-coordinate. The focusing can be automated by means of a laser or contrast evaluation in the image-processing system. The sensor controls the shift of the quill in the z-direction. The respective z-value supplements the x–y coordinates of the associated position to actual measured three-dimensional (3-D) values. Instead of autofocusing options, one can also use a direct laser measuring system for the addition of the third coordinate, for example, a triangulation sensor. This method forms a laser point on the surface of the workpiece. Using observational optics arranged at a defined angle with respect to the sensor, a difference in the height of the surface of the workpiece is recorded directly. When the measuring range of the triangulation sensor is not sufficient, one can extend its application range by shifting with the quill. The measured *z*-value can then be calculated from the *z*-axis of the measuring system and the measured value from the triangulation sensor.

One very new and interesting sensor variation is the fiber-optic sensor patented by Werth Messtechnik (Fig. 14.24). It consists of an extremely small glass sphere, which is suspended by a glass fiber. Over this light pipe, the sphere can be directly illuminated. To capture the measuring points, the glass sphere is placed on the workpiece to be measured. The image-capturing system (CCD matrix) can detect this probe either in transmitted light or through its self-lighting. The center of the sphere describes the coordinate of the measuring point, just as for normal mechanical probes.

The *software* in the attached computer essentially has the following tasks:

- Capture of the measuring points
- Corrections, for example, perpendicularity and guideway deviations of the measuring machine components, probe radius and middle point, probe bending, temperature influences
- Coordinate transformations, for example turntable and workpiece coordinate systems
- The calculation of ideally geometric substitution elements from the measuring points
- The combination of single elements
- Conversions, projections, etc.
- Evaluation (nominal-actual comparison), protocol, statistics.

Device control (point or path-control, scanning) comes with the computer numerical controlled (CNC) coordinate measuring machines.

For the archiving of results or for further processing, data transfer by means of a network is possible.

Proceeding with the Measurement

The completion of a measuring task by means of coordinate measuring machines is explained in the following. Three phases will be differentiated.

Phase 1: Planning. The planning phase can be done remotely from the measuring machine, but requires knowledge of the technical possibilities, the available probes and clamping elements as well as extensive experience. Especially this phase is decisive for a metrologically safe and economically justifiable execution of the measuring task. The test task, which is generally fixed on the drawing, forms the basis for the planning of the measurement. Differences in the path arise, whenever the aims of the measurement (evaluation of the part), quality-orientated production control, or check for assembling possibility are changing. In this case, knowledge about the production of the piece (for example, the machining base) or its later application (subsequent machining and assembly) is useful. The test task is divided into its single elements and combinations. A sequence from easiest to most complicated is then sought.

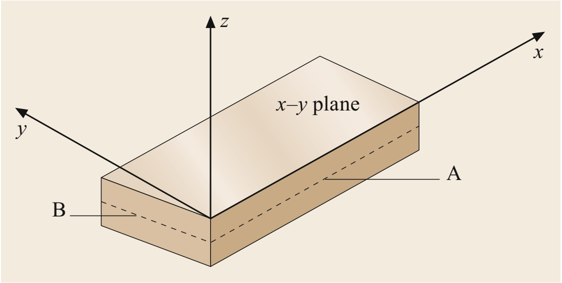


Fig. 14.27 The workpiece coordinate system

It is advantageous to specify a coordinate system on the workpiece not only for the measurement, but also for the evaluation of the results. This workpiece coordinate system must be clearly described mathematically. To do this, the following steps are required:

1. Space adjustment: description of a coordinate axis (mainly *z*) as the main direction of important form elements (for example, the direction normal to a surface, the axle of a cylinder). The *z*-axis is described in the example picture (Fig. 14.27) by the normal to the upper workpiece plane.
2. Plane adjustment: hindering the rotation of a coordinate system around these under point 1 defined axes (for example, by fixing to an edge or the straight line connecting the middle of two holes). The direction of the *x*-axis in the example picture (Fig. 14.27) is defined in the *x*–*y* plane by the corresponding direction of the long rectangular surface (dashed line A). This fixes also the direction of the *y*-axis, which must be orientated at a right angle to the *x*-axis.
3. Point adjustment: definition of the origin for *x*, *y*, and *z*. The origin of the *z*-axis through the measured *x*–*y* plane and the origin for the *x*- and *y*-axes through the intersection of lines A and B are described in Fig. 14.27.

The probe element must be chosen so that all of the elements to be measured are reachable. For this reason, more probing elements may be necessary, as shown

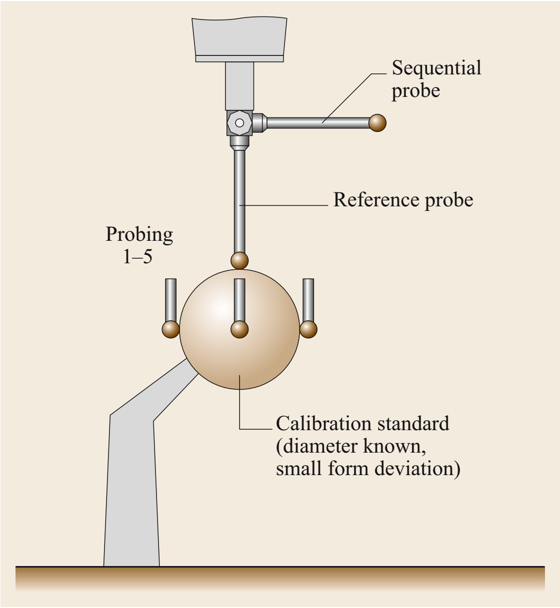


Fig. 14.28 Probe setup and calibration

in Fig. 14.28. One calls the connection of more than one probe element a probe combination or a probe tree. It can also occur that different sensors are needed for a particular measuring task. In the preparation for the calibration, a probe element is specified as a reference probe element. With multiple probe combinations or sensors, there is only one reference probe. Whenever more probe combinations are necessary, the work is implified by an automatic probe-changing mechanism.

The workpiece is set or clamped onto the measuring machine table, so that it lies as firmly and clearly as possible. Easy clamping elements, clamping element component systems, or special clamping devices are available. All of the form elements to be measured must be reachable with the chosen probe configuration. It is not allowed to come into contact with gripping or clamping elements.

The specification of the sequence of probing essentially occurs from an economical point of view (shortest routes between the elements). The type of probing (for example, mechanical or optical, point-to-point or scanning, auto-centering) is substantially limited by the technical capabilities of the measuring machine. Remark: scanning is the independent tracing of a workpiece contour by the measuring machine. One must give a starting point, an end point, the direction, and a scanning plane. The path results from the cut of the scanning plane with the workpiece surface. The scanning speed and point density must be provided by the operator. The minimum measuring point count follows from the type of geometrical elements. The aim of measurement (parameter or form deviation) forms the basis for the definition of the real measuring point count used. With increasing numbers of measuring points, the determination of the individual form elements becomes more certain. In any case, more measuring points than the minimum should be utilized. Around two to three times the minimum point count for the recording of a measurement and its deviation is sound from a measuring technology and economic viewpoint. For form deviation, one needs substantially more points. Here, the number depends on the size of the smallest geometric portions to be recorded. The measuring points should, if possible, be evenly distributed on the measured element and, in addition, must be able to represent these form elements with the desired deviations.

Phase 2: Preparation and Measuring. The probe combination is assembled as defined and then calibrated. Figure 14.28 shows the calibration of one probe of a two-probe combination. Through measurement of a calibration standard (a sphere with a known diameter and a very small spherical deviation) with both probes, the actual diameter of the probe tips and the distance of the middle of the sequential probe sphere to the middle of the reference probe sphere in the x, y, and z-directions are determined. After clamping the workpiece the machine parameters (e.g., velocity, measuring force) are defined.

The degree of automation of the measuring machine is of deciding importance for the probing of the measuring points. For manually controlled machines, the entire course (measuring point probing and manoeuvres in space between the machine elements and gripping devices) at every single point is realized by the operator. CNC-controlled machines allow the programming of a course of motion and have an automatic drive to adopt the required positions. One distinguishes between three possible programming methods:

- By teach-in, the machine learns the course of the measuring directly from the handling of the operator, i.e., his motion. He executes the course to the points to be measured as on a manually controlled machine. This way, all of the measuring point coordinates and all necessary points for collision-free manoeuvring between the machine parts and gripping mechanisms can be recorded. Afterwards, the control system can reproduce this course independently.
- The generation of the target coordinates can take place far from the machine. In this method, all measuring coordinates and position coordinates are derived from the figures or drawing data. This procedure requires great spatial imagination from the programmer. This approach is used mostly in conjunction with teach-in portions.

- Computer-aided design (CAD) systems that have a measuring module at their disposal can directly provide measuring machine programs (compare with the next section).

Phase 3: Evaluation. The description parameters for the associated geometric elements are determined from the measuring points through compensating calculations (for example: Gauss, inscribed circle, circumscribed circle). Take note that either the measuring points or the description parameters are to correct by the calibration data (probe sphere diameter, distance to the reference probe). On the foundations of the description parameters, elements can be mathematically linked or joined with each other. So, new characteristics that describe the geometry of the entire workpiece can be developed. The parameters of the individual elements (diameter, length) and the resulting parameters from the links (distance, angle) can be compared with the nominal and tolerance data. Afterwards, the results can be represented graphically or numerically.

Integration into CAD and CAM

Coordinate measuring machines (CMM) are suitable for integration into CAD/CAM environments (Fig. 14.29). This integration is possible under two criteria.

In CAD systems, the geometric data for a new workpiece is created. With that, outstanding conditions exist for the derivation of the measuring program on the basis of this data. In addition to the data describing the workpiece, a measuring module implemented in the CAD system needs data for the possible elements of the probe combination and the gripping system. *The complete measuring program can be produced in a simulated measuring run*. It is important for later functions that the coordinate system for the description in the CAD system agrees with that for the measured workpiece on the measuring machine. The measuring program can be written in a specialized programming language for the measuring equipment manufacturer or in the manufacturer-independent universal language dimensional measuring interface specification (DMIS), depending on the measuring modules available. For integration into the measuring machine program, a special interpreter is then necessary. After successful measuring, the possibility exists for the acquired deviations to be transferred back to the CAD system, to be processed or represented. Of course, an external process through best-fit and distance determination of the CAD data is possible.

The second possibility for the integration of a coordinate measuring machine is the *digitalization of an unknown workpiece geometry*. Here, a manufactured sample forms the basis (prototype). This sample is touched in a previously-defined grid. The measuring point coordinates acquired are handed over to the CAD system. There, a surface feedback or reproduction of the data model takes place. This can then be transferred to a manufacturing machine that makes a copy of the prototype.

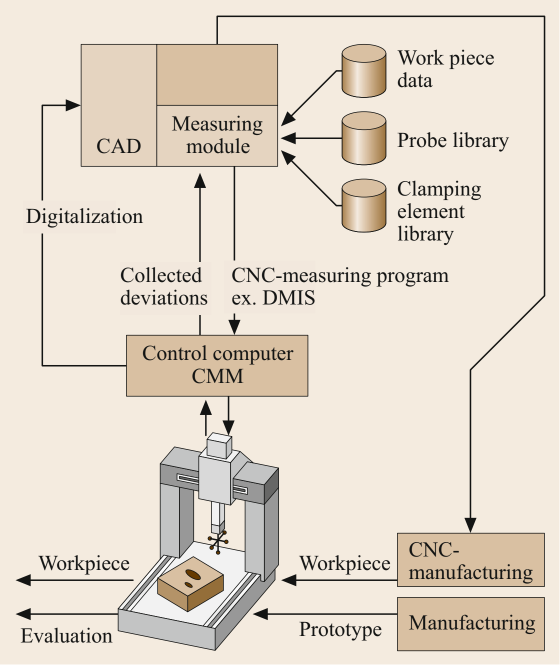


Fig. 14.29 Connection CMM–CAD

14.2.6 Surface Metrology

Instrument Technology

The surfaces of geometric objects continuously provide an informative testing object. Considerations include appearance, evaluation of the expected functional behavior, and manufacturing and wear conditions. The application of modern measuring devices in conjunction with sophisticated computer technology facilitates detailed evaluations and conclusions, which were unthinkable only a few years ago. With the equipment available and the demands of the user, these approaches are being widely applied.

Small, independent, portable instruments with skid pick-up systems are easily implemented to directly monitor tooling processes. In addition, stationary laboratory instruments with free probing systems, with correspondingly large measuring ranges and higher resolutions, have become established. Figure 14.30 shows the basic construction of a stationary surface metrology instrument. It consists of a base and pillar. The

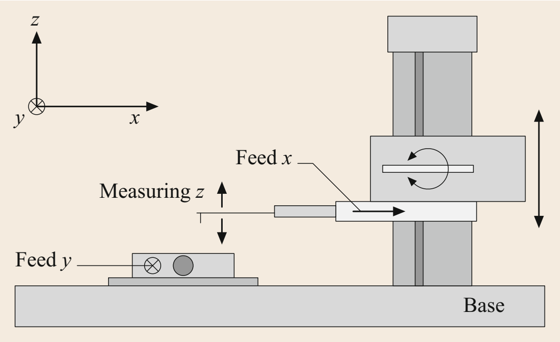


Fig. 14.30 Stationary surface metrology instrument

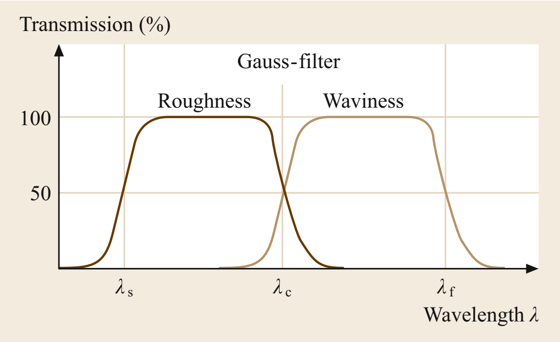


Fig. 14.31 Roughness and waviness profiles

feed unit, attached to the pillar, can be positioned aloft and be pivoted opposite the base. The probing system is positioned with high precision on the feed unit. This positioning constitutes the measuring basis for the probing of a measuring object. If required, the system can be supplemented with an additional y-table. This y-table facilitates the step-by-step movement of the workpiece perpendicular to the feeder movement, enabling three-dimensional scanning.

Instruments constructed as component systems allow a surface probing system to be used as a contour probing system (larger measuring range, many different types of possible probes) and, therefore, to expand the application range of the instrument considerably. It is also possible to implement, instead of a mechanical probing system, a noncontact probing system if the surfaces are sensitive to mechanical probing. One option is to use autofocusing laser sensors (Sect. 14.2.8).

Developments in electronics over the last few years have made it possible to digitize large quantities of data with a higher decimal precision (a higher number of levels) with sufficient speed. This has enabled the collection of many measuring points (with a smaller distance between measuring points at an acceptable collection speed) over larger measuring ranges with greater resolution (small Δz). The accessories for roughness measuring instruments range from stylus stop attachments to a large selection of speciality probing elements and various skids. The instrument can be tailored to the measuring task with these specialized accessories. As well as instrument equipment, the environmental conditions are also an important aspect to consider. The implementation in the laboratory setting, in contrast to the factory floor, brings with it a significant improvement in environmental conditions. This facilitates tasks with greater demands for precision.

ISO Standards and Consequent Requirements

The relevant ISO standards give not only the definition of characteristics but also requirements on the measuring instruments (e.g., the probe-tip radius, the distance between measuring points) and software (e.g., a phase-correction Gauss filter). The profile, which is obtained by means of the section probing method, is called, after the application of the filter for short wavelengths λ_s, the primary profile (P-profile). The roughness profile (R-profile) is obtained through the deletion of the long-wavelength profile features (threshold wavelength λ_c) from the primary profile. The waviness profile (W-profile) is made by filtering the primary profile by means of λ_c and λ_f, as is depicted in Fig. 14.31.

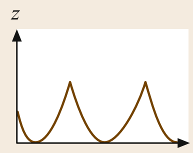
The cut-off wavelengths λ_c and λ_s required for this filtering can be seen in Fig. 14.32 according to the profile classification between periodic and aperiodic. Currently, no concrete definition exists for the threshold wavelength λ_f, only the recommendation of $\lambda_f = 10(5)\lambda_c$. Besides the threshold wavelengths for the separation of profile elements, definitions of the maximum probe element radii and the distances between measuring points are being established. However, there are severe restrictions for the use of instruments in this way.

Characteristics can be calculated from all profile types (P, R, W). Figure 14.33 shows the arrangement of surface characteristics based on the example of the roughness profile. Fundamentally, horizontal, vertical, and hybrid characteristics can be differentiated. These are supplemented by characteristic curves from which parameters can be derived.

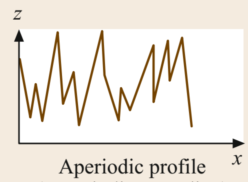
Because the explanation of the single characteristic definitions would be too lengthy, the corresponding standards (ISO 4287 [14.15]) is referred to instead.

Analysis of a Surface

Whereas the previously explained, easy-to-handle instruments with skid pick-up systems can only collect and evaluate roughness, instruments with reference-surface probing systems produce data that, with proper software, can measure not only roughness and waviness characteristics but also size, form, and positional deviations. Also, a description of surface alterations by



Periodic profile (ex. lathing, milling)



Aperiodic profile (ex. grinding, eroding)

Average ridge width of the roughness profile RSm (mm)	Measuring conditions: Threshold wavelength λ_c (mm)	Threshold wavelength λ_s (µm)	≈ Ratio λ_c/λ_s	Single measured length lr (mm)	Measured length ln (mm)	Probe length lt (mm)	Maximum tip radius r_{tip} (µm)	Maximum point distance Δx (µm)	Arithmetic mean of roughness Ra (µm)	Maximum profile heigh Rz (µm) $Rz1_{max}$ (µm)*
0.013 < RSm ≤ 0.04 ►	0.08	2.5	30	0.08	0.40	0.48	2	0.5	◄ (0.006) < Ra ≤ 0.02	(0.025) < Rz ≤ 0.1
0.04 < RSm ≤ 0.13 ►	0.25	2.5	100	0.25	1.25	1.50	2	0.5	◄ 0.02 < Ra ≤ 0.1	0.1 < Rz ≤ 0.5
0.13 < RSm ≤ 0.4 ►	0.80	2.5	300	0.80	4.00	4.80	2; 5	0.5	◄ 0.1 < Ra ≤ 2	0.5 < Rz ≤ 10
0.4 < RSm ≤ 1.3 ►	2.50	8	300	2.50	12.5	15.0	5	1.5	◄ 2 < Ra ≤ 10	10 < Rz ≤ 50
1.3 < RSm ≤ 4 ►	8.00	25	300	8.00	40.0	48.0	10	5.0	◄ 10 < Ra ≤ 80	50 < Rz ≤ 200
Additional for RSm to all profiles	Phase correct Gauss-filter						∢ 60° (90°) 0.75 mN		For Ra, Rq, Rsk, Rku, RΔq	For Rz, Rv, Rp, Rc, Rt (*for $Rz1_{max}$ ...)

Fig. 14.32 Measuring conditions (ISO 3274 [14.13] and ISO 4288 [14.14])

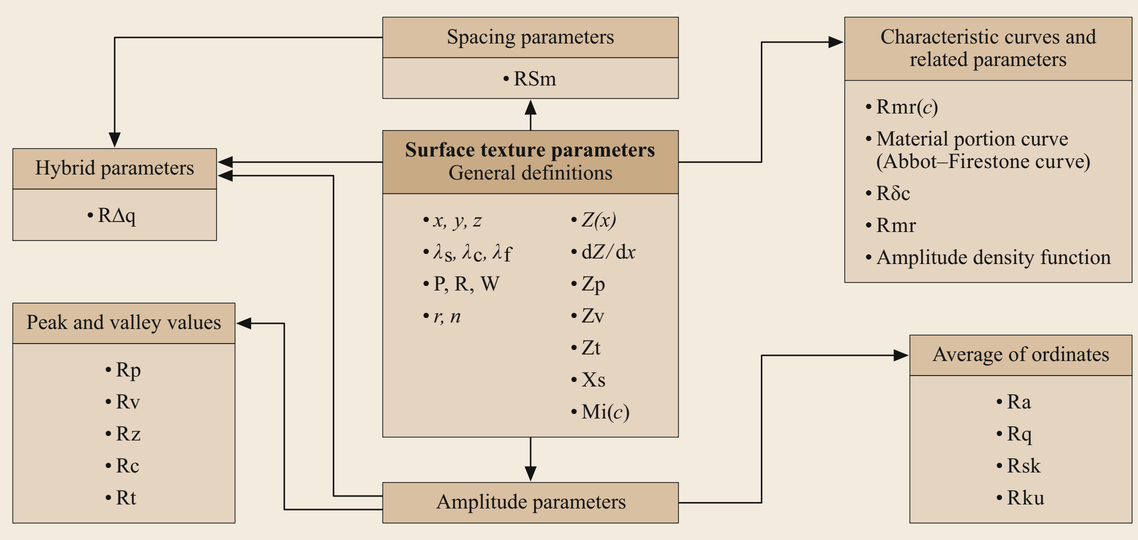


Fig. 14.33 Surface texture parameters (ISO 4287 [14.15])

abrasion and coating, amongst other effects, is possible with these systems.

The difference in the information content of the data is immediately recognizable in Fig. 14.34. Whereas the skid pick-up system only captures the roughness portion approximately, a slant and curvature can be recognized in the data collected from the reference-surface probe system. The skid pick-up system manages with essentially small measuring ranges and poor guidance, which makes these instruments much more affordable. However, one should pay attention to the fact that the mechanical filtering of the signal, by means of the skid, cannot be removed during the follow-up evaluation.

The larger information content collected with a reference-surface probe system is accompanied by substantial disadvantages related to the instrument technology. The disadvantages are the relatively large measuring range of the probing system, which is required

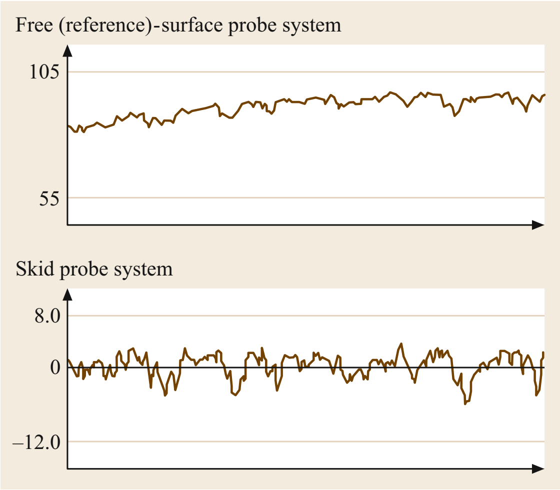


Fig. 14.34 Primary profile

in order to obtain the primary signal within a justifiable adjustment effort, and the fact that the straightness of the feed unit movement must be very good, as it contributes to the measuring signal. Both effects lead to relatively high instrument costs.

Figure 14.35 shows the example of the implementation of surface metrology equipment with a reference-surface probing system. At the top, data collected from a partially coated workpiece is shown. The implementation of a probe element with a comparatively large radius ($r = 500\,\mu m$) leads to the low-pass mechanical filtering. For the compensating calculation, only data that represents the uncoated material is used. After this calculation, the course of the layer thickness between the measured profile and the extended compensation profile is clearly recognizable in the coated section. Similar approaches are also suitable for wear measurement whenever unworn workpiece sections are still available. On the lower part of Fig. 14.35, production progress is shown by a double profile. The basic result is a turning surface profile, which is then smoothed in a second processing step. Clearly, the varying manufacturing results achieved by changing the machining parameters (low or optimal pressing force on the tool) can be noted.

The additional assembly of a y-shift table perpendicular to the actual feed direction (Fig. 14.30) allows the collection of data from flat, three-dimensional structures. With the use of an appropriate software package, one can derive three-dimensional surface characteristics from this data, or rather a visual impression of the surface for the benefit of the user. This allows conclusions on properties of the surface, which one cannot easily derive from a single profile. Figure 14.36 shows the three-dimensional measured structure of a workpiece

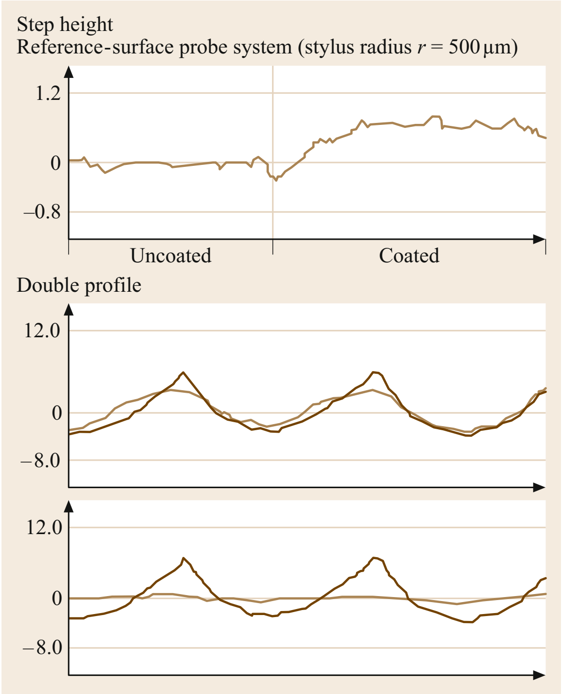


Fig. 14.35 Application for the manufacturing measurement technology

that was milled with a spherical-headed milling tool. In the left-hand side of the figure, a detail from the actual surface is shown. The differences in altitude are represented by different brightness. There is also the choice of an isoline representation (connected lines of equal height). The curvature left behind by the spherical cutter is clearly recognizable. Under this relatively strong curvature, the detailed structure remains hidden.

The right-hand side of Fig. 14.36 shows the same section. In order to make the details clearer, the dominating curvature in the left part of Fig. 14.36 is removed with the use of a compensating calculation (a three-dimensional, second-order polynomial fit). Now the milling feed is clearly recognizable. The unclear structure in the middle of the illustration emerges because there are no definite cutting properties in the domain of the center of the cutting tool.

14.2.7 Form and Position Measuring

Instrument Technology

Form inspection equipment in most cases consists of a base and a column. A turntable is integrated into the base. An arm that carries the measuring system is located on the column. Even after construction of the instrument, the turntable, the column, and/or the arm can be arranged as a measuring base. In most cases,

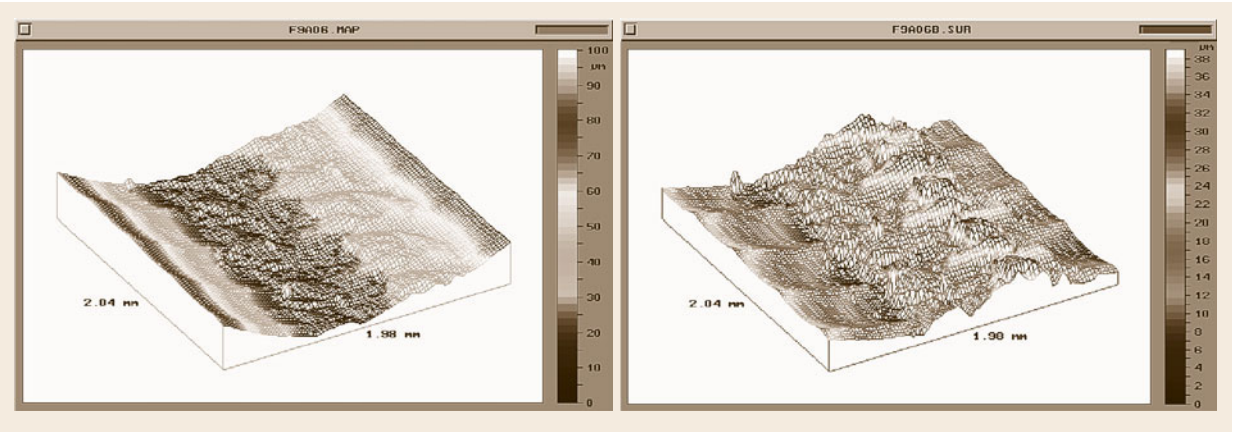


Fig. 14.36 3-D surface structure

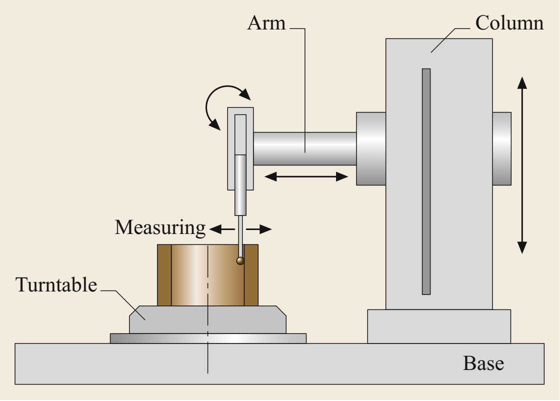


Fig. 14.37 Form inspection instrument

the measuring system is inductive. Probing is carried out with a spherical probe element. In order to keep abrasion to a minimum, ruby probing elements, as used in coordinate measuring machines, are utilized. The measuring system is inclinable so that the direction of the measuring force can be reversed. Therefore, almost all necessary measuring points can be reached. Figure 14.37 shows a vertically arranged probe system, by which the measuring force from the workpiece acts radially outwards. Subject to the measuring task, one or more feed axes can be implemented.

Measuring Execution

Figure 14.38 shows, in the upper left-hand corner, a roundness inspection. After positioning the piece on the turntable, the piece is orientated to the rotating axis so that the measuring system remains in the measuring range during the course of inspection. With a large measuring range, visual judgement suffices for orientation. The large measuring range leads to a bad resolution. A more accurate orientation of the piece is demanded for a smaller measuring range, which directly leads to a better resolution.

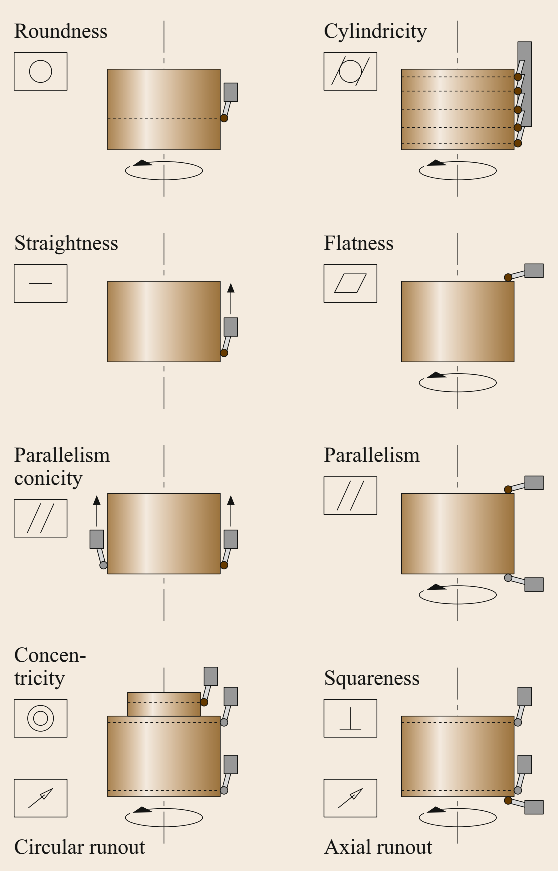


Fig. 14.38 Measuring execution

After the probe is brought into contact with the desired position on the object, the measuring object is rotated 360° by the turntable, and, while the object is

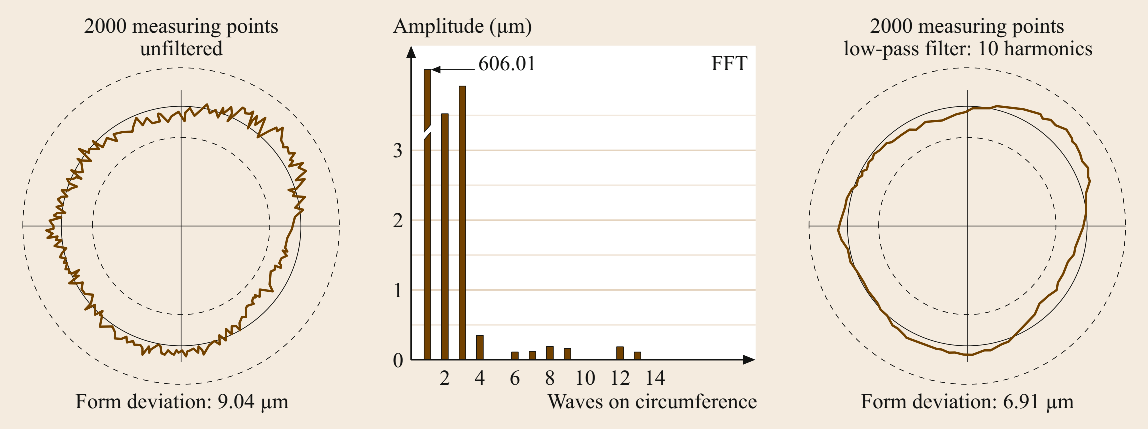


Fig. 14.39 Roundness deviation

turning, the measuring points are scanned. An ideal circle is calculated from the measuring points. For this, depending on the aims of the inspection, compensating methods (e.g., Gauss, circumscribed circle, inscribed circle, see Sect. 14.2.5) can be chosen. In reference to the compensating circle, the range between the lowest point and the highest point is the roundness deviation. For the investigation of causes of deviations, one can filter the desired frequency domains or use a frequency analysis, e.g., a fast Fourier transform (FFT) (Fig. 14.39).

On the left-hand side of Fig. 14.39, the unfiltered circular form deviation is depicted for evaluation of the workpiece. The frequency analysis in the graph next to it shows that waves, especially with a period of two and three harmonics, dominate the result. The right-hand side of Fig. 14.39 shows the measuring result after running the data through a low-pass filter (limit wavelength of 10 harmonics). Here, it is easier to recognize causes of deviations and to implement corresponding quality-orientated corrective action into the manufacturing process.

Figure 14.40 shows the collection of cylinder form deviation. Here, in addition to a high-precision rotating axis, a column axis with a correspondingly small straightness deviation is used in order to facilitate vertical movement. When positioning, movement of the arm should be avoided. All of the measuring points collected, located on circles, are put through a compensating calculation together. From the distances between the single measuring points and the compensating cylinder, the cylinder form-deviation is derived.

Just as the number of points on a circle is important for the determination of the circular form deviation, the number of measured circles for the cylinder-form deviation is not to be neglected. In Fig. 14.40, a picture that used three circles is shown on the left, and a picture that used 13 circles to calculate the cylinder form deviation is shown on the right-hand side. Clearly, there is a noticeable difference in information content between the two.

Fig. 14.40 Cylinder form deviation

To detect referenced elements, like for example, the concentricity depicted in Fig. 14.38, one uses methods already known from coordinate measuring technology. First, both of the circles on the lower cylinder are probed. The circles should have the largest possible distance from each other in order to reduce the measuring uncertainty. Compensating circles are calculated from the corresponding measuring points. The line that connects both midpoints of the circles serves as the reference axis. After the inspection of the circle on the smaller cylinder and the corresponding determination of the parameters of the compensating circle, the eccentricity is calculated as the distance between the midpoint of the circle and the reference axis. The tolerance zone for the concentricity describes a circle around the reference axis.

14.2.8 Laser Measuring Technology

Due to its properties, laser measuring technology has gained a strong position in the field of integrated measuring technology inside the manufacturing processes. In this section, a few examples are explained and the advantages and disadvantages highlighted. The application profiles of laser measuring systems are as different as their parameters and range from simple dimensional completeness checks to high-precision measuring systems that determine surface roughness or even the acceleration of tooling machine components. From the many possible implementation variations, only a few are considered, those that use the various properties of light. After the time-of-flight method, which is not commonly implemented in mechanical engineering applications, come uses of such properties include linear propagation, reflection, or interference. The selection of the best sensor for the specific application and the arrangement of the sensor to the measuring object is based on criteria such as:

- Operating distance
- Measuring range
- Resolution (scale value)
- Measurement uncertainty
- Measuring spot diameter
- Light color and intensity.

Of course, the price of the complete system which consists of sensor, evaluation electronics and possibly components for moving the measuring object, is also relevant.

In addition to the technical and scientific considerations, protection against accidents is also an issue that should not be ignored. Because most laser measuring systems are equipped with low-power lasers (hazard category 1–3), skin burns are rather improbable. However, the eyes must be well protected. Reflected radiation from metallic surfaces is also problematic. The mandatory guidelines, for instance in Germany, demand labeling for hazard category 3B and above, the application of opaque enclosures, laser protection eyewear, and special warning and emergency facilities.

Laser Applications in Measuring Technology

The *linear propagation* of a laser beam is used by a whole range of measuring devices. To clarify this application, two examples are presented. The first is a laser scanner (Fig. 14.41), which amongst other applications is used here for the quick scanning of the diameter of shafts.

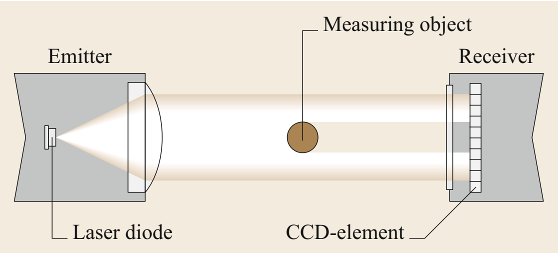


Fig. 14.41 Laser scanner

The laser beam, created by a diode, is expanded into a fan shape and aligned so that the beam is parallel. As shown in Fig. 14.41, this alignment is done by optical components. There are also laser scanners in which the beam expansion occurs by means of a spinning polygonal mirror. The laser beam is directed toward the measuring object. Behind the measuring object, a receiver is arranged where the laser beam strikes a light-sensitive CCD line array. Because the laser beam is broken by the measuring object, in this case the shaft, the size of the shadow on the receiver can determine the diameter of the object. The emitter and receiver can be adjusted axially to the shaft very quickly, so that in a short time, the diameters of various shaft sections can be determined.

A second application of linear laser expansion is shown in Fig. 14.42. The emitter, which emits a laser beam with a narrow diameter, is arranged on the fixed part of a tooling machine base. The receiver is assembled on the sliding bed and consists of a CCD matrix sensor field (in the middle of the figure). Different manufacturers also use four quadrant diodes at this location as a receiver.

Now, the sliding bed of the tooling machine is steered to its home position. The point at which the laser beam strikes the sensor field is registered (y_1, z_1 at $x_1 = 0\,\mathrm{mm}$). On the way to the end position, it is stopped at defined points, and for each stop, the laser point is registered on the sensor field (y_2, z_2 at x_2, and so on). From the points obtained, the straightness deviation of the sliding bed movement is shown divided into the x–y and x–z planes.

A laser beam reflected by the measuring object is generally used by laser distance sensors. These are employed for the contactless measurement of deformable, very rough, sensitive, hot, or moving surfaces. A laser autofocusing sensor and a laser triangulation sensor are given as application examples. Figure 14.43 shows schematically the construction of an autofocus sensor

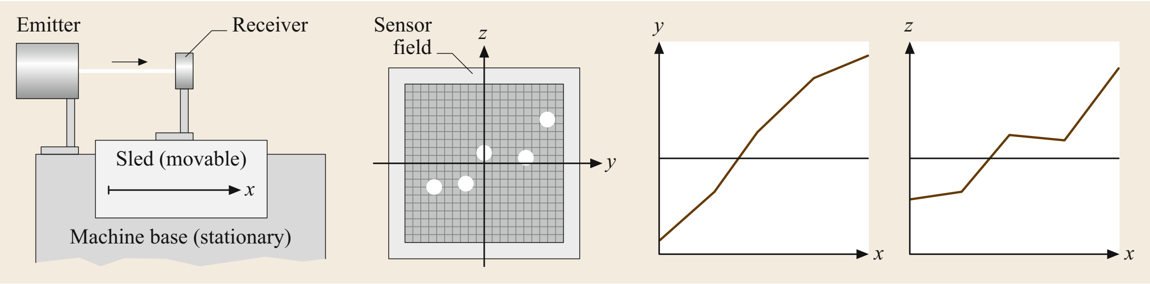


Fig. 14.42 Alignment measuring system

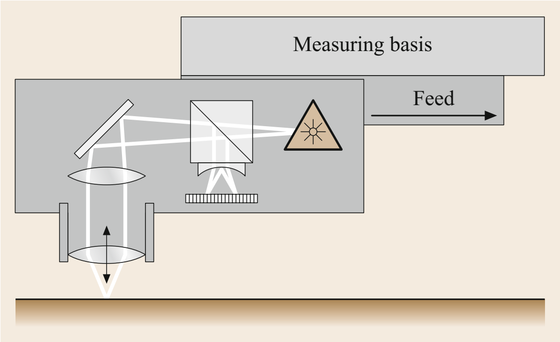


Fig. 14.43 Autofocus sensor

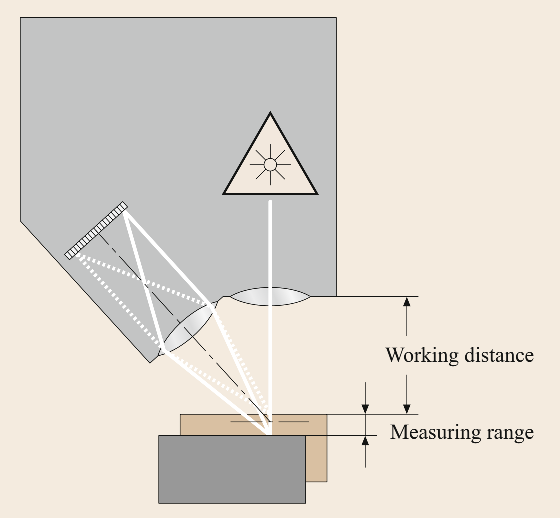


Fig. 14.44 Triangulation sensor

(Mikrofokus from UBM). The laser beam is projected onto the surface of the measuring object, and the laser beam is reflected from this surface. Specialized electronics monitor the focusing and, when necessary, readjust the lens system. The displacement of the lenses is recorded as the measuring value. The previously-mentioned sensor example has a working distance of about 5 mm and a measuring range of 1 mm. The laser spot focused on the surface of the measuring object has a diameter of 1–5 µm, while the beam has an angular aperture of 30°. The electronics used in the example allow the measuring signal to be broken up into steps of 16 nm. With these parameters, the sensor is well suited for contactless surface inspection. The advantages of noncontact probing are also accompanied with disadvantages. Problems especially arise due to locally strong reflective materials (for example, single grains on grinding wheels) and also by nonreflective materials, as well as by steeply inclined surfaces (over 30°). In these cases, the reflected beam cannot be collected for evaluation. The reaction of the system to such problems is variable (measuring value setting, holding or searching) and must be taken into consideration by evaluation of the signal.

Triangulation sensors (Fig. 14.44) likewise project a light point onto the surface of the object measured. This light point is observed from a defined angle. By changing the distance between the sensor and measuring object, the reflected point wanders across a CCD row. This way, the change of the distance is collected directly. In addition, some sensors project one or many laser lines onto the surface inspected. These lines can then be evaluated in terms of the contour of the measuring object by means of a CCD matrix.

The example sensor chosen has an average working distance of 105 mm, a measuring range of ±25 mm, a projected laser spot diameter of 0.1 mm, and a triangulation angle of 18°. With these parameters, these sensors can be applied, for example, to:

- Size or form inspection
- The collection of runout and position deviation
- The collection of thickness
- The collection of deformations
- Completeness or integrity control.

As Fig. 14.45 shows, single or combined sensors are necessary for these applications. The measuring signal collects the surface of the measuring object in the range of the entire measuring spot diameter. So, a low-pass

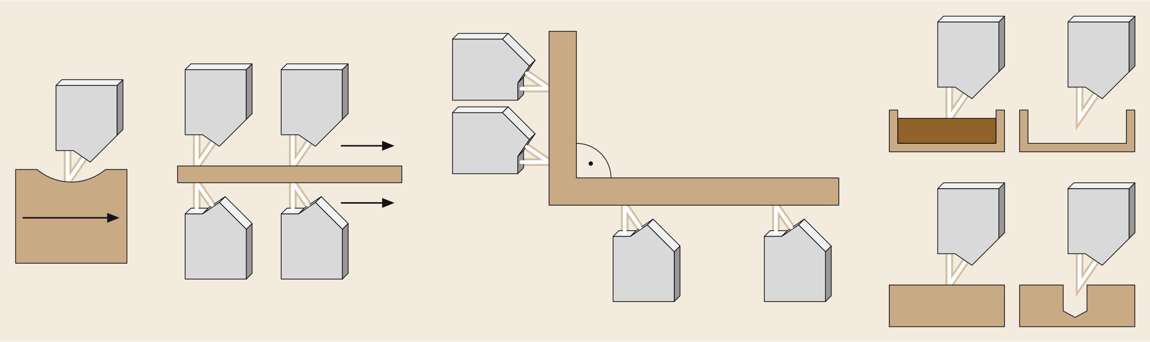


Fig. 14.45 Examples of applications using triangulation sensors

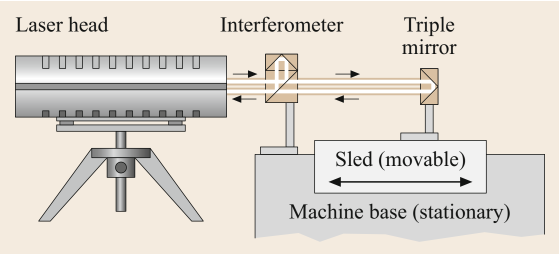


Fig. 14.46 Interferometer for the determination of position

filter processes and determines the mean distance in this area. The plane in which the beam is sent and reflected is arranged parallel to the surface structure to guarantee a reflection.

In laser interferometers, the laser beam is separated into two beams (reference and measuring beam) by means of a semireflecting mirror. While the reference beam always follows the same path inside the interferometer, the measuring beam is reflected off a triple mirror on the object to be measured, as shown in Fig. 14.46. When the two beams come together, interference occurs (Fig. 14.47). When the peaks of the waves meet (phase shift 0°), the light is amplified. When the peak of one wave meets the valley of the other (phase shift 180°), the waves cancel. The distance between the interferometer and the triple mirror changes when the sled moves. The phase between the reference and measuring beam shifts. This resulting change in the interference is interpreted as the measuring value.

This type of measuring system is used for applications with large lengths (10–20 m) and with a high resolution (5 nm). In each case, it only collects the changes from an initial state. A disadvantage is that the optical components must be mounted on the object that is to be measured and that the frequency of the light, and therefore the measuring result, is strongly influenced by environmental conditions such as air temperature, humidity, and pressure. Corrections can be made by collecting these environmental conditions and carrying out a subsequent adjustment of the data, or more specifically, through the application of a refractometer (an instrument in which the effects of the environmental conditions can be directly compared with the light properties in a vacuum).

Figure 14.46 shows an example combination that determines the position of a machine component with

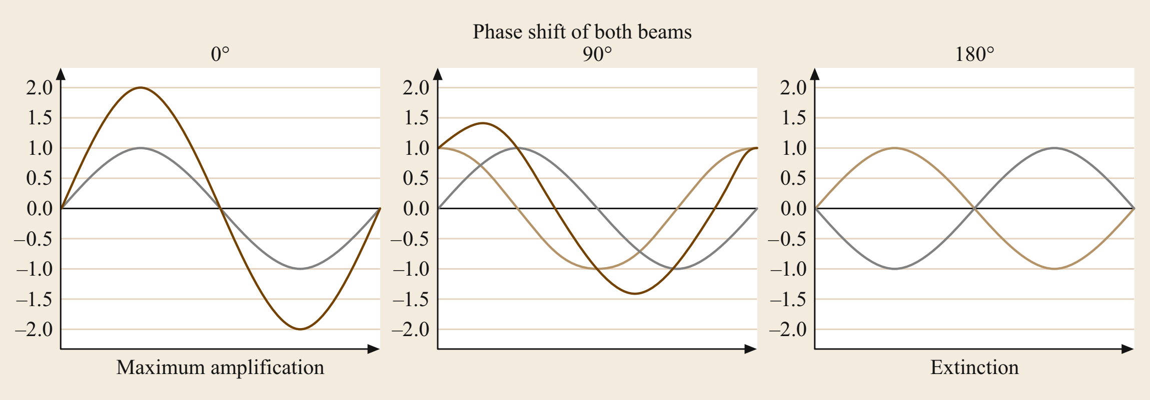


Fig. 14.47 Phase shift and interference

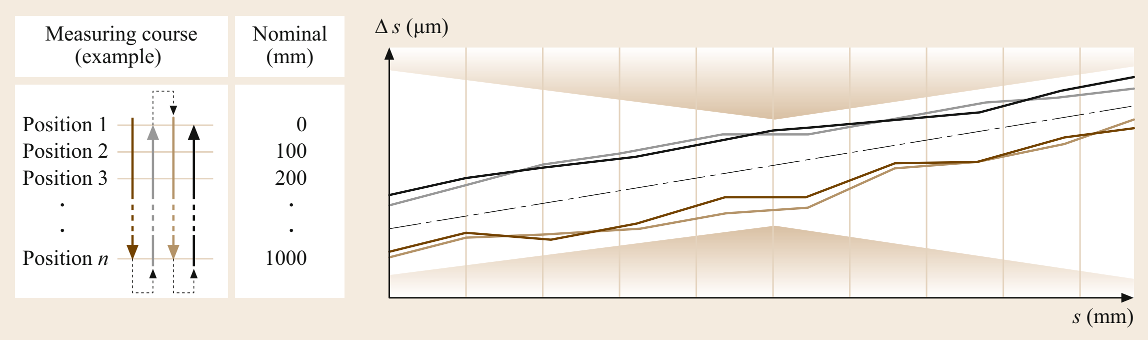


Fig. 14.48 Position deviation, measuring course, and results

respect to another, or rather to a chosen fixed point. This setup is used as an independent measuring system (for example, with coordinate measuring machines) but also as a measuring system for the collection of position deviations. Figure 14.48 shows the procedure for the collection of position deviations of a tooling machine. While the machine, controlled by its measuring system, follows the defined positions labeled 1 to n, the position deviations are determined by means of a laser interferometer. The measuring course, which is executed step by step over the entire range of the positions to be measured, is completed multiply in both directions (increasing and decreasing values). The deviances collected in this way are shown on the right-hand side of Fig. 14.48. From the depicted course of measuring values, a linear trend and span superimposed with random sections can be read. The limits shown in the diagram depict usual tolerance ranges for tooling machine position deviations. The systematic parts are compensated for, when necessary, through mechanical aligning of machine components, or afterwards by means of a correction table or correction function.

Similar arrangements allow the collection of tilt and rotation angles, as well as the determination of straightness deviations. When the measuring value transmission frequency can be chosen to be sufficiently large, a dynamic series (for example, the reaching of a desired position) can be collected with the layout shown.

14.2.9 Measuring Uncertainty and Traceability

The result of measuring is the measurement value. This measurement includes the true value and also systematic and random deviations of the measurement (Fig. 14.49). It is possible to estimate the expected value of the measurement by calculating the arithmetic mean of several independent measurements. The more single values that are processed, the more the random parts of the measuring deviation are reduced.

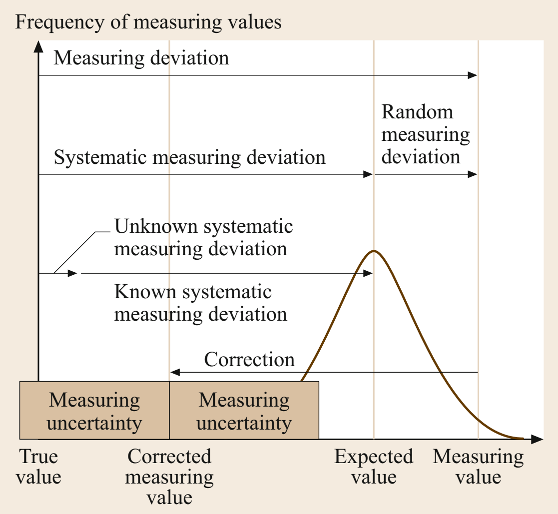


Fig. 14.49 Summary of measuring values

The systematic part of the measuring deviation can be determined by measuring an object with a known value. Such objects, measurement standards, are measuring blocks for lengths. Angles can be represented with angle gauges, precision polygons, or with sine bars used in conjunction with measuring blocks. The known value of the measurement standard (whose small deviation from the true value is negligible for the purpose of comparison), is called the correct value. The systematic measurement deviations can be calculated from the difference between the measured value of the measurement standard and its correct value. Afterwards, one can correct all measuring values by use of the known systematic deviation. The nonmeasurable or not measured (for instance, because it is too expensive) elements of the systematic measuring deviation are combined with random measuring deviations to constitute the measuring uncertainty. So, the measuring uncertainty is a parameter obtained from the measurement. It describes the region around the corrected measuring value where the true value must be found. The complete result of measuring is given as the corrected measuring value plus/minus the measuring uncertainty [14.16].

In order to guarantee the correctness of measuring results, measuring devices must be affiliated to the national standard of the respective measurement. In Germany for instance, this is the National Physical Technical Institute (PTB), located in Braunschweig, which is responsible for the representation and propagation of physical units. Through the PTB, calibrating laboratories are accredited, so that their measuring devices and measuring standards coincide with the national standards (the units), according to the defined and accepted techniques. These are the laboratories of Germany's national accreditation body (DAkkS), former German Calibration Service (DKD).

All in-company measuring devices, or rather standards, should be consistently traceable back to the national standard of the PTB (Fig. 14.50). In order to verify this, the instruments are calibrated by a DAkkS laboratory or the PTB themselves. *Calibration* is defined as the inspection of measuring devices and measurement standards with reference to the accepted national standard. Successful calibration is generally documented through a protocol, the calibration certificate. On the calibration certificate, all of the calibration results, the

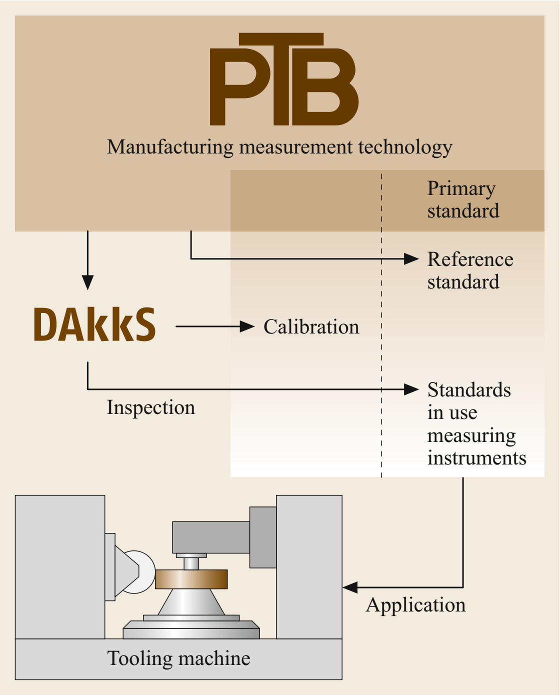


Fig. 14.50 Traceability

reference standards, and additional measuring equipment (used during the calibration), the environmental conditions, and the calculated measuring uncertainty are documented.

One should use certified instruments, standards, and methods in order to achieve cost-effective, in-company control of inspection instruments. Otherwise, a traceability certificate is not possible.

The setting-up and balancing of a measuring instrument, by which known systematic deviations of the measuring result are eliminated, is called *adjusting*.

14.2.10 Inspection Planning

Inspection planning means the planning of quality inspection in the entire production process, from the arrival of raw products to the delivery of the final product. For this, inspection tasks and procedures are specified with inspection feature, inspection location (close to production, measuring room), frequency of inspection, point of time within the production process, inspection methods, inspection equipment, and operators. One should consider both technical and economic aspects. The inspection planner must consider knowledge of the function and application of the piece or the components, safety hazards, the production process, technical documentation (drawings, standards, stipulations), and the inspection equipment. It should be consistently checked that the data is complete, current, and inspected (approved by the operating department).

For the selection of the test methods a systematic search in the drawing(s), in the work plan, in the documentation, in delivery instructions and in contractual agreements, is required. When searching in drawings it is possible to search according to the type of parameter (dimension, shape and positional tolerance, surface tolerance, etc.), according to the drawing view and/or according to grid squares (e.g. starting at the top left, clockwise).

The definition of the inspection frequency (number of samples, sample size) occurs on the basis of mathematical statistical facts. The time point in the production process allows company organizational and economical considerations. The late recognition of inadmissible errors can bring about several disadvantages.

The definition of inspection methods and inspection equipment are related, and, thus, should each be chosen with the other in mind. The choice of measuring device begins with a consideration of the required information content of the measuring result. This way, the aim of the inspection (evaluation of workpiece or process, manufacturing control) and the impact of the measuring instrument itself can be taken into account. Geometrical limitations, such as the accessibility of the piece, the geometry of the probing element, the range of measurement (direct measurement, difference measurement) of the instrument, and especially for soft materials, the measuring force, have been previously decided upon. Finalized statements for the usability of a measuring instrument can be made after inspection of the scale division value and the measuring uncertainty. The measuring uncertainty must adhere to the ratio of the inspected tolerance by the relation $U/T = 0.1$–0.2. Alternatively, it is possible to obtain measuring capability coefficients and check the adherence of these characteristics to previously defined limits [14.17]. Supplemental criteria are, for example, the surfaces available for the measurement and transfer for processing, protocol, and archiving.

The required measuring time (capability of the measurement to be automated) in conjunction with the number of pieces to be tested is the essential criterion for the cost effectiveness of the application of a measuring device. Included in the inspection costs are also the equipment costs, equipment observation, calibration, and personnel costs (work time, education).

To guarantee the comparability of the measuring result and low uncertainty of the acquired characteristics the following conditions should be taken into account when specifying measurement methods:

- Explicit guidelines for the measuring procedure, including the parameters required for an appropriate measurement. Specification of the reference basis for the measuring procedure, the accuracy of the applied measuring instruments and measurement standards, gripping elements employed, and additional measuring equipment.
- Details of the measuring strategy, for example, the definition of the measurement location on the piece, or the number and arrangement of single measurements as a basis for a good average value.
- Details of the measuring value collection method for selective inspection and of the further steps of measured value processing, or guidelines for the application of analyzing software (for example, the selection of a compensating method).
- Legal warranty of adequate qualification of the personnel conducting the measurement.

The result of inspection planning is the inspection plan.

14.3 Further Reading

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14.3 ISO 9001: 2015-09 Quality management systems – Requirements (Beuth, Berlin 2015)
14.4 ISO/TS 9002: 2016-11 Quality management systems – Guidelines for the application of ISO 9001:2015 (Beuth, Berlin 2016)
14.5 ISO 9004: 2018-04 Quality management – Quality of an organization – Guidance to achieve sustained success (Beuth, Berlin 2018)
14.6 IATF 16949: 2016-10 Quality management system requirements for automotive production and relevant service parts organisations (Beuth, Berlin 2016)
14.7 ISO 286-1: 2010-04 Geometrical product specifications (GPS) – ISO code system for tolerances on linear sizes – Part 1: Basis of tolerances, deviations and fits (Beuth, Berlin 2010)

14.8 ISO 286-2: 2010-06 Geometrical product specifications (GPS) – ISO code system for tolerances on linear sizes – Part 2: Tables of standard tolerance classes and limit deviations for holes and shafts (Beuth, Berlin 2010)

14.9 ISO 2768-1: 1989-11 General tolerances; part 1: tolerances for linear and angular dimensions without individual tolerance indications (Beuth, Berlin 1989)

14.10 ISO 2768-2: 1989-11 General tolerances; part 2: geometrical tolerances for features without individual tolerance indications (Beuth, Berlin 1989)

14.11 ISO 1101: 2017-02 Geometrical product specifications (GPS) – Geometrical tolerancing – Tolerances of form, orientation, location and run-out (Beuth, Berlin 2017)

14.12 H. Linke, J. Börner, R. Heß: *Cylindrical Gears: Calculation – Materials – Manufacturing* (Hanser, München 2016), Chap. 8: Assuring the accuracy of cylindrical gears

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14.14 ISO 4288: 1996-08 Geometrical Product Specifications (GPS) – Surface texture: Profile method – Rules and procedures for the assessment of surface texture (Beuth, Berlin 1996)

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