Chapter 2
Metrology and Workpiece Quality

2.1 Manufacturing Disturbances and Manufacturing History

The basic task of manufacturing is to provide workpieces with specified quality characteristics in the required quantity in the most time- and cost-efficient way possible. Every manufacturing process is affected by variable disturbances, which can be both external and internal (occurring within the process itself). For this reason, the functionally determinative properties of the components are provided with tolerances. If a characteristic value lies outside of the permissible tolerance, it is defective. Thus important functional characteristics must be tested either already during manufacturing or at the end of manufacturing. Important disturbance factors which must be taken into consideration as possible causes of defects are: disturbances caused by static forces, such as deflections effected by the workpiece weight or clamping errors; disturbances caused by dynamic forces which lead to either self-starting or forced oscillations; disturbances caused by thermal influences, such as process heat or internal sources of heat in the machine tool; and disturbances caused by tool wear (Fig. 2.1). This group also includes disturbances resulting from the engagement kinematics between the tool and the workpiece, such as generated cut deviations occurring during hobbing or diffraction effects on optical surfaces caused by systematically applied tool marks.

Functionally determinative quality characteristics can be defined through macro-geometrical properties. Macro-geometrical properties include, for example, the accuracy of dimension, form and position of geometrical elements. Micro-geometrical parameters include, for example, characteristic surface values, such as roughness, mean roughness value and polishing depth. However, the functional integrity of the process requires that certain properties are tolerated although they lie below the surface in the peripheral surface zone. These may include hardness values, residual stresses or certain structural properties.

The fluctuations of characteristics occurring in every manufacturing process can basically be derived from the influence of either systematically or randomly occurring disturbances. Systematic errors are caused by the system. They are reproducible under identical boundary conditions and change the characteristic in a single direction; they cause manufacturing trends. Systematically acting disturbances cause deviations in characteristics. If the causes of systematic errors are known, they can

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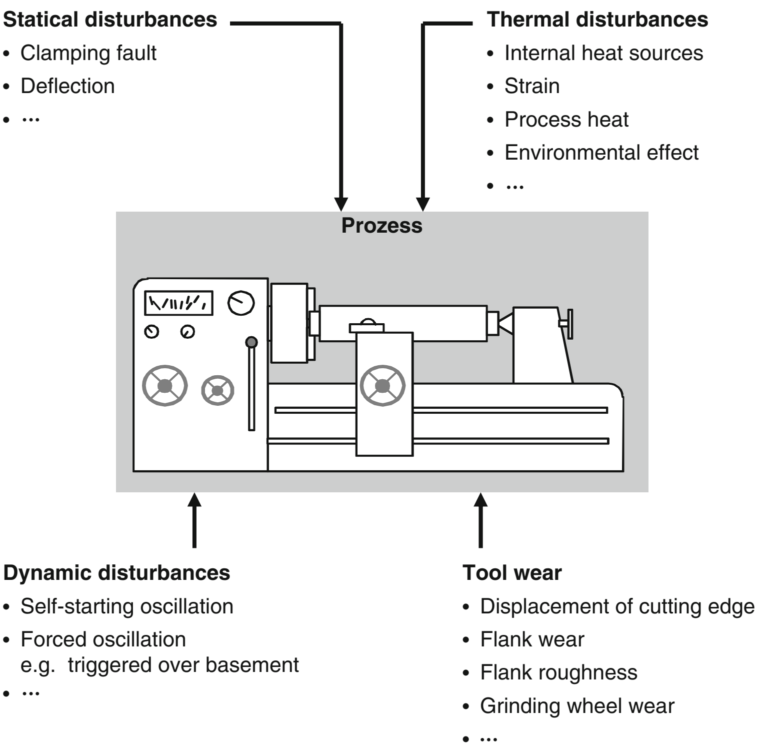


Fig. 2.1 Variable disturbances in manufacturing

be corrected and compensated. Examples of systematic errors are geometric errors of machine guiding elements and the development of cutting edge offset through the continuous wear of turning tools used in turning processes. Changes of the cutting force caused by sudden cutting depth fluctuations and the workpiece deflections associated with them may also be of systematic nature (Fig. 2.2).

Randomly occurring disturbances lead to changes to characteristics, the effects of which cannot be predicted in a strictly deterministic way. They influence the result in both a positive and a negative direction. Thereby, the work result becomes unstable. The influence of random disturbances on the work result can, however, be statistically recorded. Examples of this include fluctuations in the structure of a material, random temperature fluctuations or sudden self-starting oscillations (rattling oscillations). Within real processes, it is not always easy to clearly decide between systematic and random influences.

An important parameter describing the effect of random disturbances on a quality characteristic (i.e. on the variation of a quality characteristic) is process capability or the process capability index (Fig. 2.3).

These process capability indices can only be applied if the variation of the characteristics are normally distributed. In practice, it is frequently required that $c_p \geq 1.33$. The process capability index is always taken as the dominant process

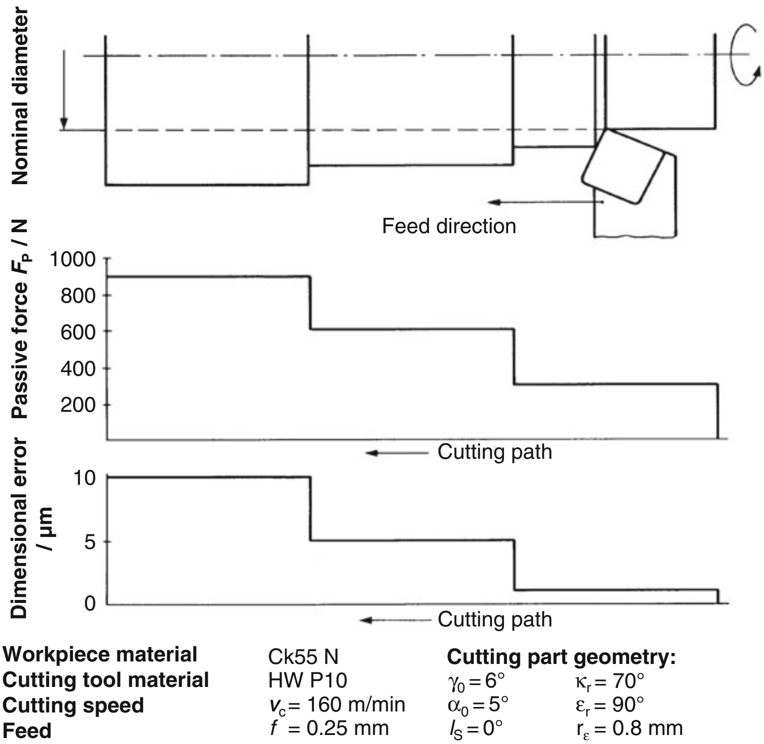


Fig. 2.2 Influence of passive force on dimensional accuracy

design criterion when large numbers of pieces must be manufactured with the highest possible level of productivity. Variation in manufacturing batches occur, when it can not be guaranteed that all active elements work securely during the process being at its performance limits. If, for example, cutting edges are randomly failed during a cutting process because of cutting edge fractures or layer failures, this can have an immediate, significant on the process capability. Another example of critical process conditions is when the quantities of heat entering the workpiece at high process performances cause thermal strain to induce an increased variation of geometrical characteristics. These examples reveal that measuring and testing procedures in manufacturing are necessary both to guarantee the quality of the manufactured part and to start and develop processes.

In general, several manufacturing steps are necessary to manufacture a part. Manufacturing progresses result from a manufacturing chain or a manufacturing sequence. With every manufacturing step, characteristic changes (geometry, surface, peripheral surface zone) are left behind on the part. Thus a manufacturing history develops (Fig. 2.4). The output properties of the part following a certain manufacturing step in turn become the input factors for the processing steps which follow. There can also be a significant interaction between the current step in the process and previous changes.

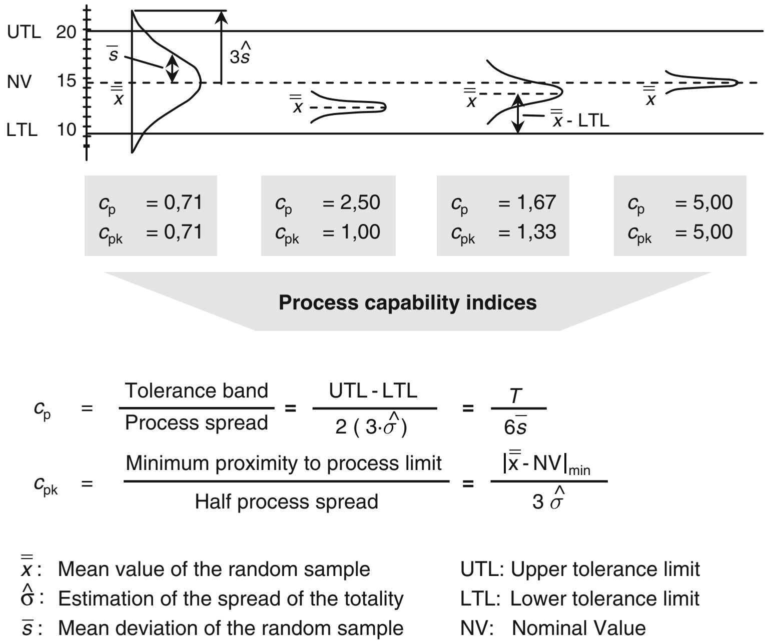


Fig. 2.3 Process capability indices

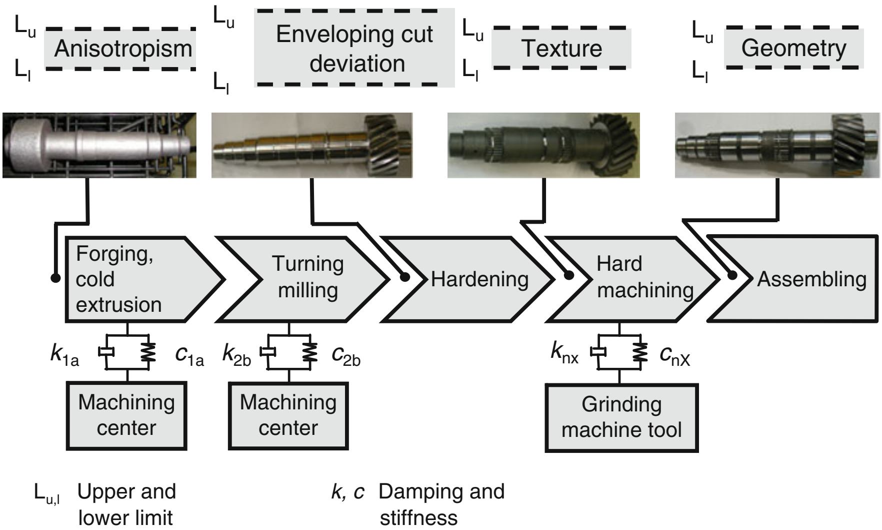


Fig. 2.4 Manufacturing history (Source: Getrag Ford)

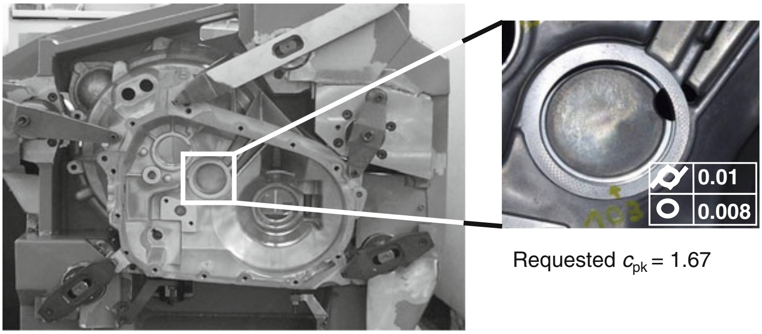


Fig. 2.5 Representative case study – box part

The hole in a transmission part shown in Fig. 2.5 could not be manufactured in a procedurally secure way with the required process capability index and specified. There can also be a significant interaction between the current step in the process and previous changes. The hole in a transmission part shown in Fig. 2.5 could not

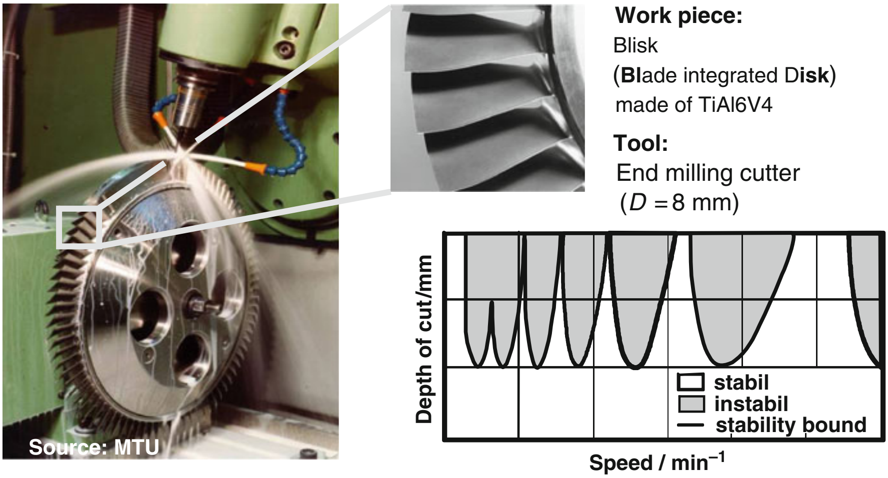


Fig. 2.6 Stability bounds when milling a BLISK

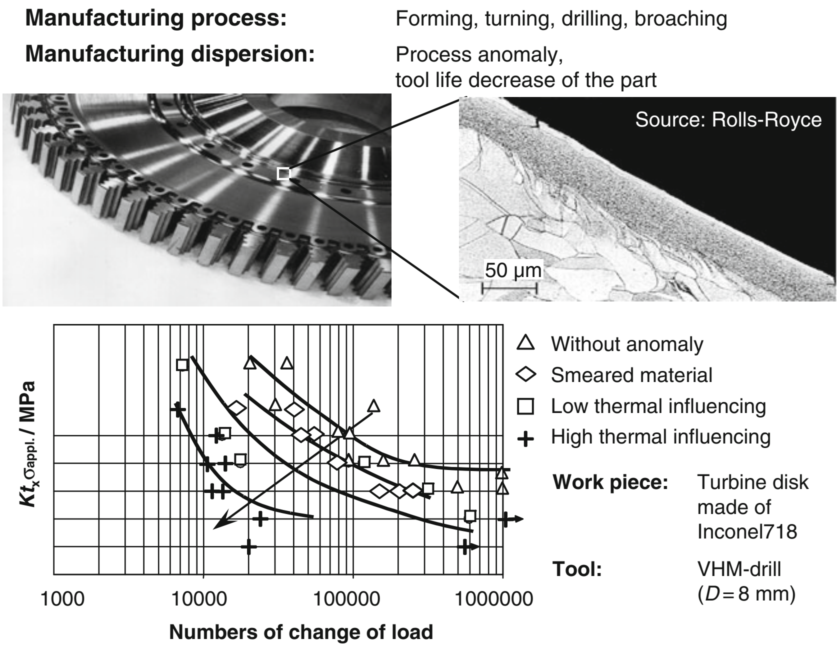


Fig. 2.7 Surface damages when drilling with a worn drill

be manufactured in a procedurally secure way with the required process capability index and the demanded productivity. This is due to released residual stresses which arised in the previous die-casting process.

Figure 2.6 shows a part manufactured by milling with long, slender end mills.

The milling process is only stable for certain combinations for cutting speed and depth of cut. When these areas are exceeded, rattling oscillations occur. These characteristic stability areas must be known; otherwise the process cannot be carried out at the performance limit.

However, not only impermissible macro-geometrically or micro-geometrically recognizable changes may limit the process, but also impermissible changes in the peripheral surface zone. Figure 2.7 shows a turbine disk which was exposed to high mechanical and thermal stresses caused by machining the drill holes. These stresses damaged the peripheral surface zone in a way that significantly diminished the fatigue strength of the part.

2.2 Measuring and Testing

Quality characteristics must be tested during the manufacturing due to the boundary manufacturing conditions mentioned above. This can be done by means either of samples or of a 100% test. A 100% characteristic check is prescribed for many safety-related parts. Though, a 100% test does not assure freedom of errors.

Testing means determining whether the test sample exhibits the required characteristics, such as dimension, form and surface quality. This determination can be made in different ways, thus the distinction between *subjective testing* and *objective testing*.

Subjective testing is performed by means of the sensory perception of the tester, e.g. visual and tactile tests. Examples of this are the evaluation of burr formations on the edges of parts and of shadings on polished surfaces.

In objective testing, the tester is supported by testing equipment. There are two further methods which fall under this category; measuring and gauging.

Measurement is the comparison of a characteristic with a measurement standard. The result is a measured value. Gauging is the comparison of the test object with a dimension or a form. The result is information regarding whether the specified requirements were satisfied or not (go or not-go).

Testing equipment is subdivided into measuring instruments, gauges and aids. Measuring instruments and gauges are distinguished by material measures corresponding to the measurand. Material measures can be of mechanical, electric, optical and electronic nature. Mechanical material measures may be, for example, distances between surfaces or angular positions of surfaces. Indicating measuring instruments have movable markers, divisions or counters. When using these devices, the measured value reading can be either direct analogue or digital. In contrast to this, the gauge body corresponds merely to the dimension or the dimension and form of the required characteristic. Intermediate values cannot be defined.

Table 2.1 provides a survey of the attainable accuracy values when using different manufacturing processes.

Table 2.1 Survey of manufacturing qualities

	Standard tolerance IT															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Primary shaping											■	■	■	■	■	■
Die forming (warm)									■	■	■	■	■	■	■	■
Extrusion (cold)							■	■	■	■	■					
Deep drawing					■	■	■	■	■							
Turning					■	■	■	■	■	■						
Drilling								■	■	■	■	■	■			
Reaming					■	■	■	■								
Milling						■	■	■	■	■	■	■				
Grinding	■	■	■	■	■	■	■	■								
Erosion		■	■	■	■	■										

2.2.1 Measurement Errors

As a matter of principle, every measurement result is subject to error. Possible reasons for measurement errors are shown in the ISHIKAWA diagram in Fig. 2.8. The causes of measurement errors may lie in the measuring method, the measuring

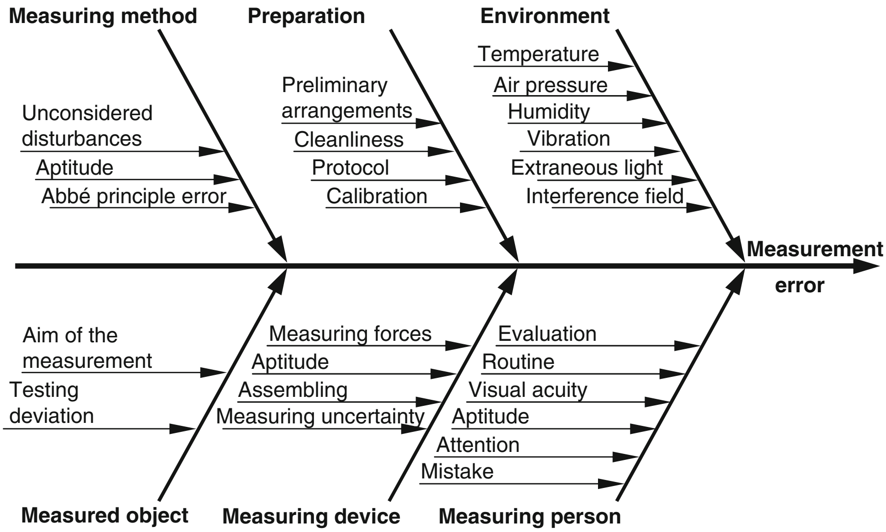


Fig. 2.8 Causes for measuring errors by the measuring procedure

instrument, the measured object, the person measuring, the preparation involved and the environment.

In order to achieve a high measurement accuracy, it is necessary to take the abovementioned influences into consideration and, where applicable, to minimize them, compensate them, or at least to estimate them in terms of their magnitude. It can principally be distinguished between systematic and random disturbances in measurement procedures, as well [DIN1319a].

2.2.2 *Macro- and Microgeometry of Components*

2.2.2.1 Structural Deviations

With regards to components, the distinction is often made between macro-geometrical parameters and the surface quality. Macro-geometrical parameters refer to deviations of dimension, form and position. The surface quality is defined by roughness parameters. The transitions between these categories are not always clearly definable. DIN 4760 offers a general system for organizing structural deviations (Fig. 2.9). Therefore it is necessary to define the term "surfaces" at the beginning. The real surface (primary surface; see DIN EN ISO 4287) is the surface actually present on the part. The actual surface is the metrologically registered surface. It may differ from the real surface, since every measuring method can only approximate the real surface. A geometrically ideal surface is assumed in designs

Structural deviations (in superelevated representation)	
	1^{st} Order: form deviations
	2^{nd} Order: waviness
	3^{rd} Order: grooves (roughness)
	4^{th} Order: scores, scales (roughness)
Not easily representable	5^{th} Order: textural structure 6^{th} Order: lattice structures of the material
	Superposition of structural deviations 1^{st} up to 4^{th} Order

Fig. 2.9 Structural deviations, acc. to DIN 4760

and forms the basis of tolerances. In Fig. 2.9 six orders of structural deviations are defined on the basis of these observations.

Structural deviations of the 1^{st} order (see also the following sections) are frequently the result of systematic errors. With regards to waviness, i.e. the structural deviations of the 2^{nd} order, one cannot clearly define whether they are caused by systematic or random influences. The unbalance of a rotating tool and any periodical oscillations caused by it are forced, while sudden rattling oscillations are self-starting. In general, fundamentally different actions must be implemented in order to exclude any systematic or random causes of error. Structural deviations of the 3^{rd} order also occur regularly. They are to be attributed to the penetration between tool and workpiece and are often determined by means of penetration calculations. Examples of these are kinematic roughness associated with turning, surface marks created in peripheral milling and generated cut deviations created in hobbing. In such cases, the structural deviations can be influenced in a targeted way by means of generation kinematics and tool design. The higher orders of structural deviation are primarily random in their occurrence. Examples of structural deviations of the 4^{th} order include chip formation processes and removal processes. Roughness of the 5^{th} order is rendered visible by structural properties on the surface. This can play a significant role in the high-precision machining of metallic optical mirrors. Thus in high-precision turning of multicrystalline metals, grain boundaries may become visible because the individual crystals exhibit varying orientations and therefore varying stiffnesses. In this case, anisotropism of the grains becomes visible on the surface.

In general, all the structural deviations on a real surface are superposed. Filters are employed to separate roughness and waviness in a measurement process [DIN EN ISO 4287]. The following sections will treat macrogeometrical deviations of structure, form and position, as well as the corresponding measurement technology. Section 2.4 and the following sections describe the metrological recording of higher-order structural deviations.

2.2.2.2 Form Deviations

Form deviations refer to deviations from a specified ideal geometrical property, such as straightness, evenness, roundness or cylindric form [DIN EN ISO1101, VDI2601].

The following will introduce some examples of form errors and their causes (Fig. 2.10).

- A cause for deviations from the cylindric form of a workpiece can be the incorrect alignment of the workpiece on the machine tool with respect to the tool.
- Another cause for form deviations is the continuous alteration over time of the tool geometry caused by wear.
- Thermal displacements of the workpieces, tools and machine tools can also lead to form deviations.
- Deviations from cylinder form can also arise when the workpiece deflects because of a radial strain. This can happen, for example, e.g. when turning long, slender parts when the workpiece is not supported.
- Roundness errors can develop through the incorrect clamping of the workpieces on the machine tool.

2.2.2.3 Position Deviations

Position deviations are deviations of the position of a geometrical element with respect to a reference, such as an edge, circulation line or axis of the predetermined position. In general, the position of two surfaces or axes in relation to each other is indicated by simple length or angle specifications.

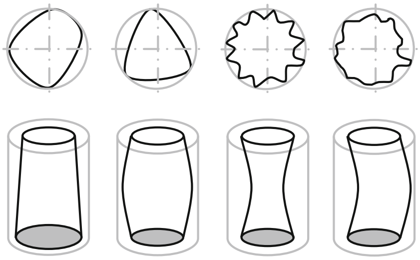


Fig. 2.10 Deviations from circularity and cylinder form

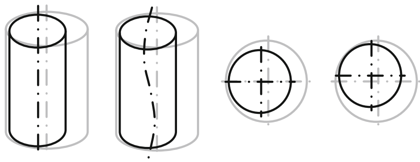


Fig. 2.11 Deviations from concentricity, straightness and parallelism

Position deviations as shown in Fig. 2.11 may arise, for example, through incorrect clamping or defective clamping devices.

2.3 Length Testing Devices

2.3.1 Material Measures

A *material measure* in length measurement technology represents lengths or angles by means of fixed distances or angles between surfaces or lines. Setting standards are material measures. The material measures used most frequently are gauges.

The most important and most precise material measures in length measurement technology are parallel gauge blocks. They consist of two plane-parallel measuring surfaces made of hardened steel or cemented carbide. Parallel gauge blocks are used in prismatic and cylindric forms. Gauge blocks are composed of grades. A standard set contains 5 grades each containing 9 blocks, from which almost any dimensions can be assembled (see Fig. 2.12). The measuring surfaces are superfinished and even enough to allow, after careful cleaning of the measuring surfaces, individual gauge blocks to be joined together so that they adhere.

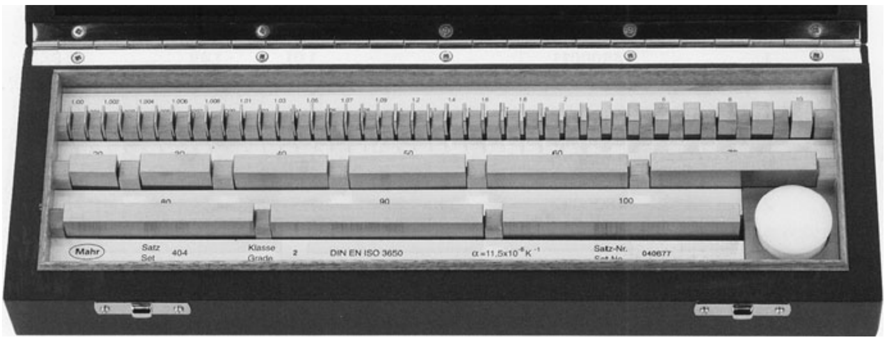


Fig. 2.12 Gauge blocks (Source: Mahr)

2.3.2 Gauges

A gauge measures dimensions or forms generally according to limit dimensions [DIN2257]. It can be distinguished between inspection gauges, limit gauges and form gauges (Fig. 2.13).

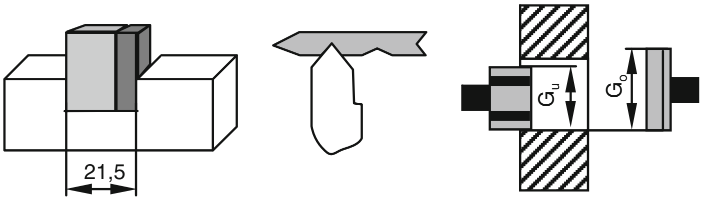


Fig. 2.13 Types of gauges: inspection gauges, form gauges, limit gauges

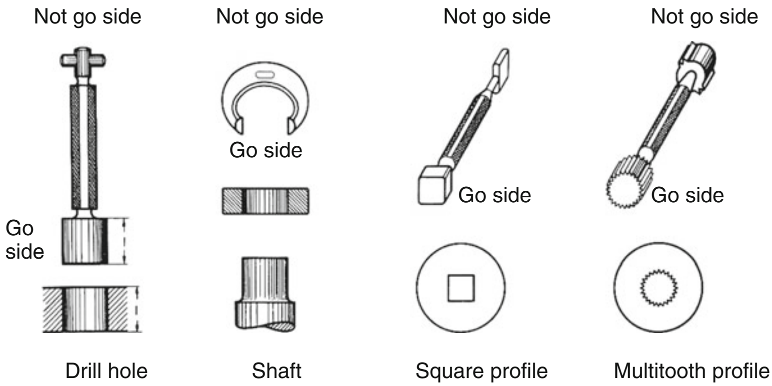


Fig. 2.14 Different types of limit gauges

Inspection gauges are parts of a gauge set for which the measure is assembled from the combination of gauges. Examples are the combination of parallel gauge blocks and the setting of feeler gauges.

Form gauges allow for the testing of profiles using the light-slit method. They include angles, radius gauges and thread gauges.

Limit gauges function according to Taylor's principle: The go gauge must be designed in such a way that the dimension and form of the workpiece can be inspected when combined with the gauge. *Not-go gauges* are only used to inspect single dimensions.

Limit gauges used most frequently are calliper gauges, limit plug gauges, gauging rings and thread gauges (Fig. 2.14). Gauges are the simplest testing equipment used in industrial manufacturing.

2.3.3 Indicating Measuring Instruments

Indicating measuring instruments consist of a material measure and a display mechanism. The *indicating range* is the range of measured values that can be displayed on a measuring instrument. The *measuring range* is the part of the indicating range for which display deviations lie within specified or agreed limits. The *suppression range* of a measuring instrument is the range which must be exceeded in order that the instrument can begin to display values. The *hysteresis* of a measuring instrument equals the difference of the display values determined by measuring from different directions. The hysteresis of a measuring instrument is often not constant, which means that only a certain lower limit is indicated. The reversal error is principally a systematic error. It can be compensated. The *sensitivity* of a measuring instrument is the ratio of an observable change on the measuring instrument display to the causative parameter. Using length measuring instruments, the sensitivity is defined as the ratio of the range of the indicating element (e.g. the indicator) and the range of the measuring element (e.g. the spindle or measuring arm). Conversion between the measurement range and the display may be based on different physical principles. The most frequently used conversion elements are mechanical, electrical, pneumatic, optical and electronic conversion elements.

2.3.3.1 Instruments with Mechanical Converters

Instruments with mechanical converters utilize mechanical or optical indicating elements. In length measurement technology, the most often used measuring instruments function on the basis of mechanical converters, e.g. threads, racks, gearwheels and blade segments (Fig. 2.15).

With mechanical *callipers* with sliding glideways as the conversion element, the material measure is mounted on the bar on which the display, i.e. the slider, is moved. Mechanical callipers have two different scales which can be read off against each other by the observer. The scale on the slider is called a vernier (Fig. 2.15).

In the case of *micrometers*, highly precise threads are used as converters and as a material measure. The system comprises a measuring spindle running in a sleeve, whose forward face is designed as the measuring surface and whose back end carries a ground thread as material measure. Typical thread pitches are 0.5 and 1 mm. As seen with callipers, two different scales are read off against each other. One scale is mounted on the sleeve, the other on the scale drum. In order to avoid influencing

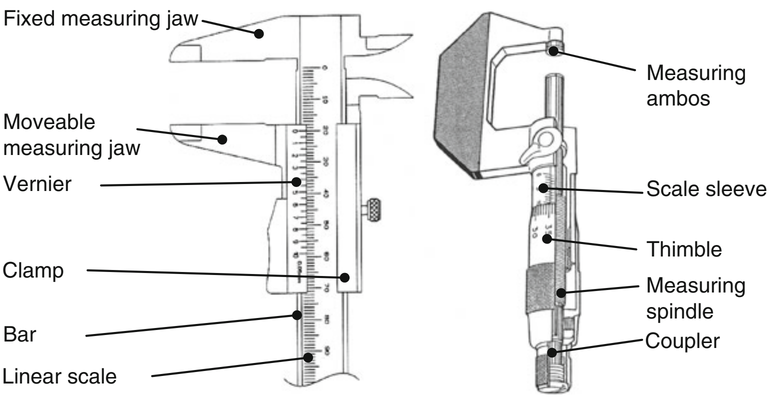


Fig. 2.15 Setup of callipers and micrometers

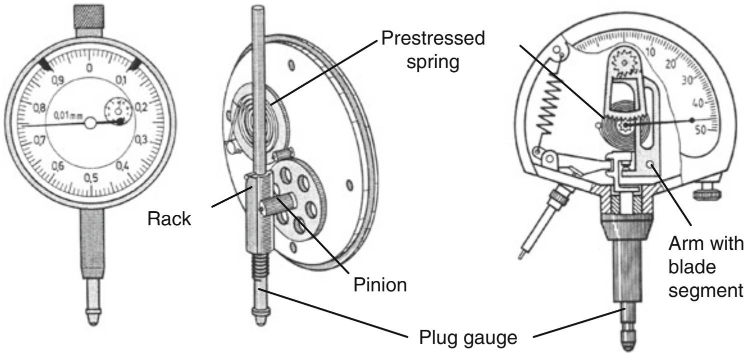


Fig. 2.16 Setup of dial gauges and dial comparator

the measurements through large fluctuations in the measuring force, the latter is limited to 5–10 N by means of a coupler (ratchet coupling). Micrometers are designed both as outside micrometers for external dimensions and as inside micrometers for internal dimensions (Fig. 2.15).

Dial gauges are length measuring instruments equipped with racks and gearwheels as conversion elements which allow a larger view of the path of the plug gauge. The material measure lies in the gear mechanism, the conversion element which leads to measurement reversal errors due to anisotropic friction and potential tolerance. Needle positions greater than 360° are possible (Fig. 2.16).

Dial comparators are the most precise mechanical length measuring instruments. They are equipped, unlike dial gauges, with a gear mechanism as lever arm system, gear segment and pinion as conversion elements. Thereby, the movement of the plug gauge is transmitted to the needle. The design only allows needle positions smaller than 360° (Fig. 2.16).

In principle, all the instruments with mechanical conversion elements described here can be equipped with frictionless optical indicator elements in order to improve precision. Given constant conversion behaviour, the more precise indications the measuring instrument should display, the longer the indicator must be. However, since there is only a limited amount of space in the instruments and, above all, since the inertia of the indicator can lead to distorted measurement results when the measurement range is small, optical indicator elements are used. The principle is basically this: a beam of light is directed to the material measure and, according to the position of the material measure, this beam is reflected in a different direction. The optical indicator then displays the measurement range of the material measure without friction and inertia.

Further potential for increasing precision can be exploited by means of a fine graduation of the scale which can no longer be observed with the naked eye, thus necessitating optical magnifying aids in the form of microscopes. By means of the microscope, a mechanism consisting of an objective and an ocular, a magnification of a real image by the objective can be viewed with the ocular. In this way, a remagnified virtual image of the object is created. The total magnification through a microscope is the product of the objective and ocular magnifications. The scale graduation can be applied in the ocular directly or by means of an ocular plate. Microscopes including measuring oculars are called *measuring microscopes*.

2.3.3.2 Instruments with Electrical Converters

These instruments are used to determine changes in the measurand caused by alterations of electrical properties, such as resistance, inductance and capacity. The turns of a coil, the distance between plates of a condensator and the resistance of an electrical conductor can all serve as material measure. Inductance, for example, is altered by changing the immersion depth of an iron core; the capacity of a plate capacitor is a function of the plate distance (Fig. 2.17).

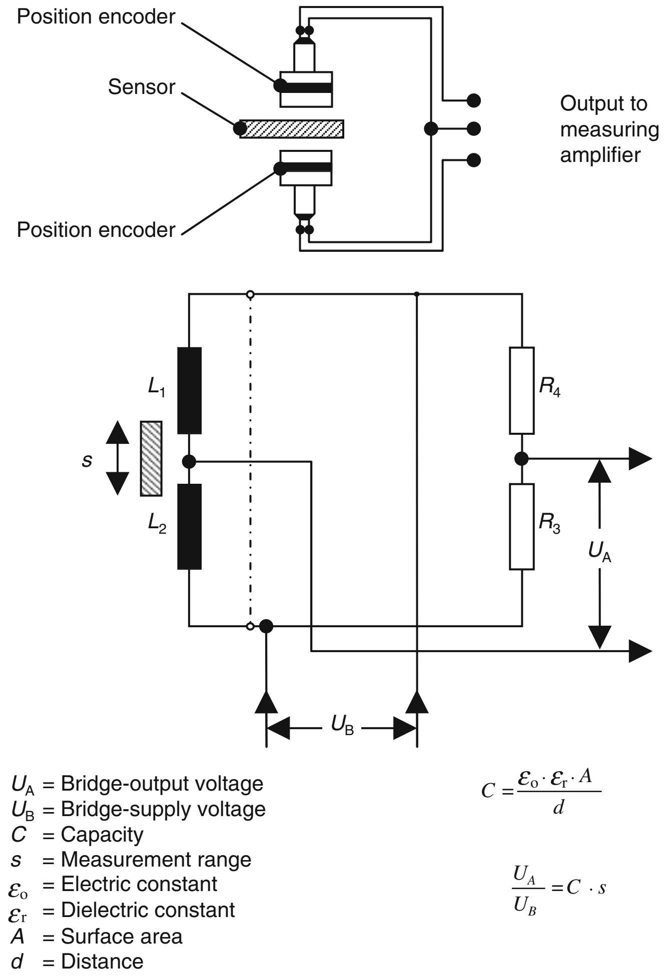


Fig. 2.17 Capacitive and inductive measuring principles

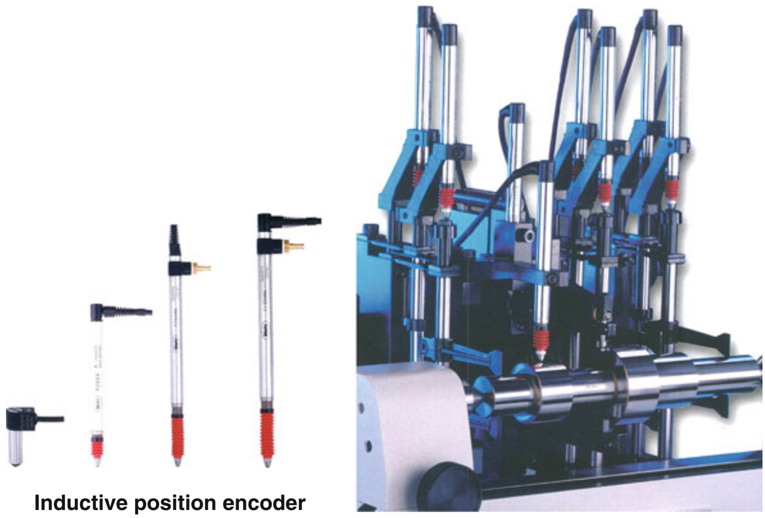


Fig. 2.18 Inductive working sensor in real execution

An alteration of the ohmic resistance can be effected by changing the conductor length and/or by a cross-sectional variation [Hoff04, Grot05]. Figure 2.18 shows a real execution for multi-point measuring with inductive working sensors.

2.3.3.3 Instruments with Optical Converters

These length measuring instruments exploit the wave property of light. The wavelength of light is used as the material measure. Figure 2.19 shows the functional principle of a laser interferometer.

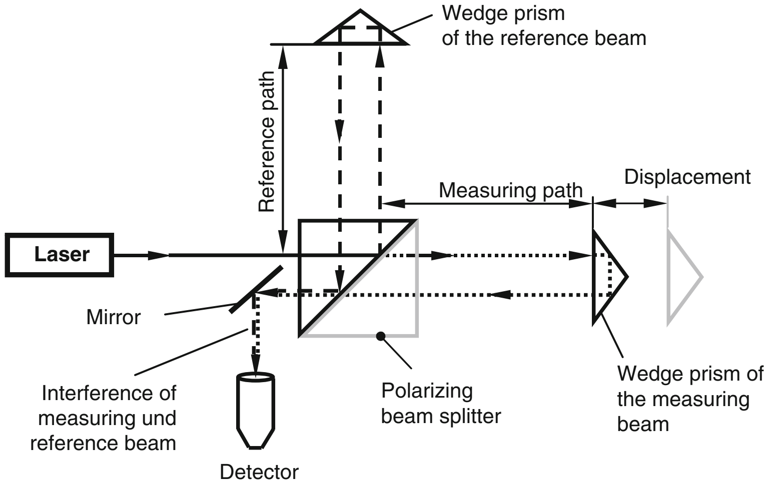


Fig. 2.19 Longimetry with laser interferometer

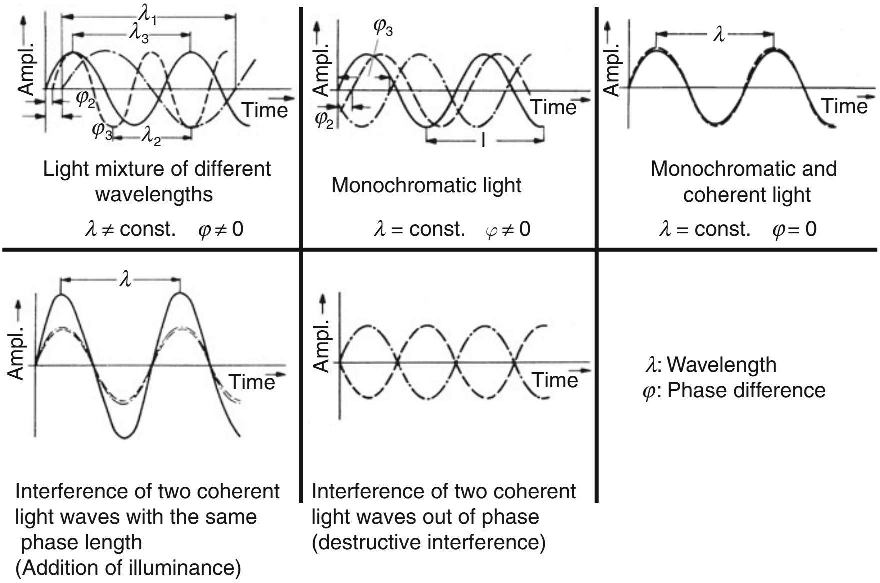


Fig. 2.20 Optical measuring principle, interference

A light source emits coherent, monochromatic light whose beam is split into a reference beam and a measuring beam at a polarizing beam splitter. These beams are reflected on a respective wedge prism and combined again through superposition. Finally, the combined beam is detected and evaluated. If the wedge prism of the measuring beam is shifted, interferences occur because of the difference of the optical paths of the two partial beams after combining them. These are fluctuations in light intensity via eliminating and amplifying light. Integral multiples of the wavelengths lead to an amplification, phase differences of 180 degrees to an elimination of light (Fig. 2.20).

The number of interference lines is directly related to the path being measured. Since the wavelength of the light is a function of temperature and also air pressure and humidity, these influences are compensated within the device. The advantages of such systems lie in their large measuring range and especially in their contactless measurements.

2.3.3.4 Instruments with Pneumatic Converters

These instruments use pressure and flow rates as material measures (Figs. 2.21 and 2.22).

This measuring principle can be used for both tactile and contactless measurement (Fig. 2.22).

There are two types of such measuring instruments: high-pressure and low-pressure instruments. High-pressure instruments work with an operating pressure greater than 0.5 bar, low-pressure instruments with an operating pressure lower than

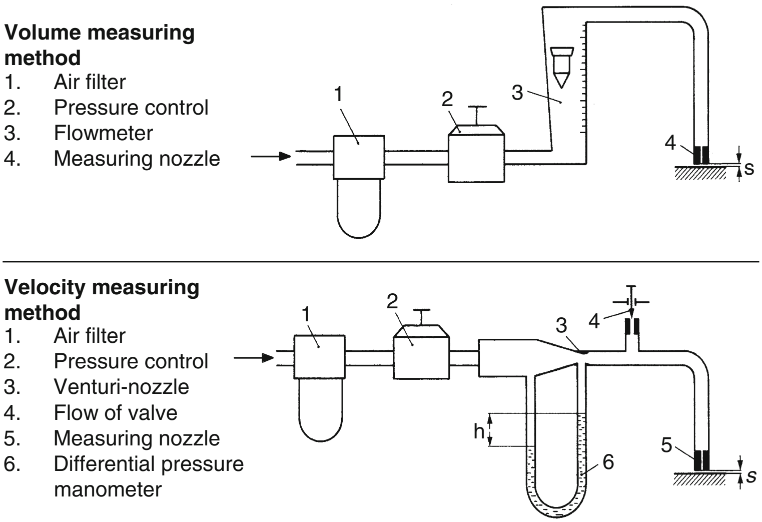


Fig. 2.21 Measuring principle of pneumatic distance measurement

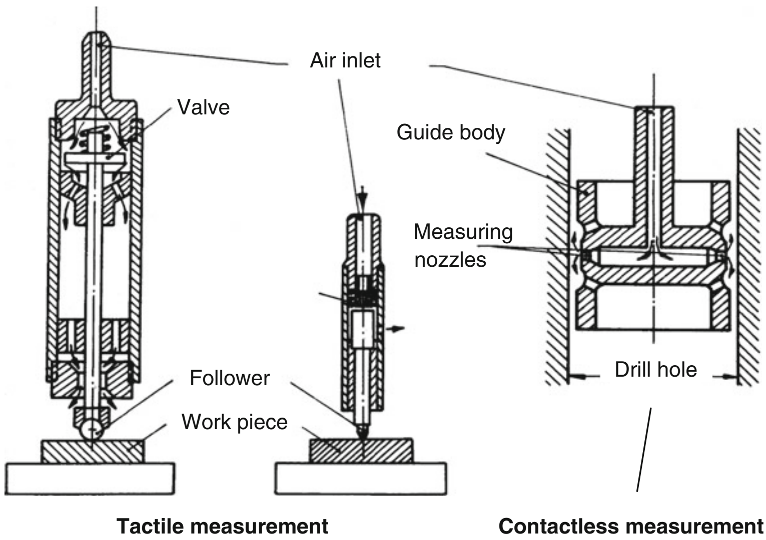


Fig. 2.22 Pneumatic sensor

0.1 bar. The pressure range between 0.1 and 0.5 bar is outside the operating range of the instrument [DIN2271a].

Figure 2.23 shows the functional principle of contactless pneumatic measurement. The left side shows an external measurement, the right side an internal measurement. If the measuring rod is designed in a way that both measuring nozzles

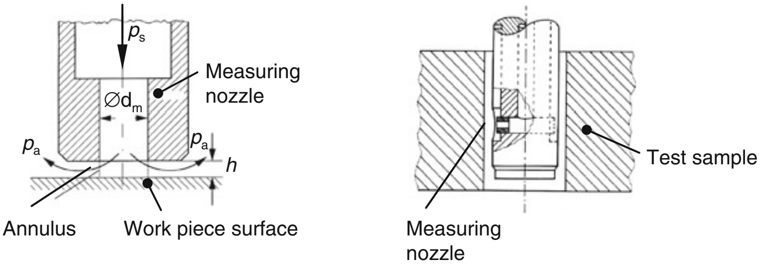


Fig. 2.23 Functional principles and examples for pneumatic measurement

work within the linear range of the characteristic diagram, then an exact centring in the hole is unnecessary, since the air currents of the two nozzles are added and the sum represent the measure for the total gap width. Since the type of hole measurement described is a two-point measurement, deviations from hole roundness and diameter can be determined by turning the rod or the workpiece.

The measuring rods are often specially adjusted to the measurement of a specific workpiece. Therefore, for economical reasons, pneumatic measurement is used predominately in serial production, especially if a 100% test is required.

The advantages of contactless pneumatic measurement lie in the self-cleansing effect of the measuring device (i.e. the workpieces do not generally have to be cleansed of oil, dirt or micro-chips) and in the quickness of the measuring process.

2.3.3.5 Electronic Measuring Instruments

These devices work with photoelectric sensors, by which light-dark fields of a gauge are converted into electric signals. The material measure is realised through the light-dark fields. Impulse gauges and code gauges are preferably used as path measurement systems. To be precise, it is a mechanical guidance system whose positions are detected and indicated optoelectronically. This path measurement system is also executed with callipers, dial gauges and dial comparators. It is also realized in coordinate measuring devices and machine tools. To control measuring axes and to evaluate data, an exact control system and effective software are required which can influence the quality of the measuring result and the applicability of the data [Pfei01]. The measurement of freeform surfaces and tooth-flank topographies on spur gears and bevel gears with coordinate measuring devices is currently state of the art (Fig. 2.24).

2.4 Surface Inspection

The task of characterizing a technical surface consists in attaining a complete topological record of its three-dimensional geometry and describing it. Often, in order to simplify the measuring process, only parameters for surface roughness along a single measured length are registered (one-dimensional parameters). This

Fig. 2.24 3-D coordinate measuring machines

procedure is frequently followed in practice and is sufficient in many cases. For certain applications, e.g. in optics or for characterizing grinding wheel surfaces, more comprehensive, multi-dimensional surface descriptions must be used. However, the following will exclusively treat one-dimensional parameters.

2.4.1 Surface Parameters

In most of the procedures used in industrial surface inspection technology, only structural deviations of the second or higher orders are analyzed and measured on surface sections. These sections must be statistically representative for the entire surface [DIN2257]. The surface can be detected by means of surface sections or the bearing surface (Fig. 2.25) [DIN4760]. Profile sections are sections which are oriented to the surface normally, tangentially or at other angles.

First, a profile section will be used to illustrate some of the basic terms of surface inspection technology (Fig. 2.26). With respect to a profile, the distinction is made between the test length L_t of the surface section being metrologically detected and

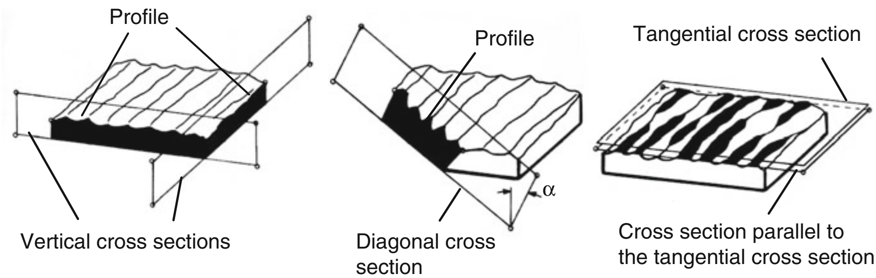


Fig. 2.25 Registration of structural deviations by surface cuts

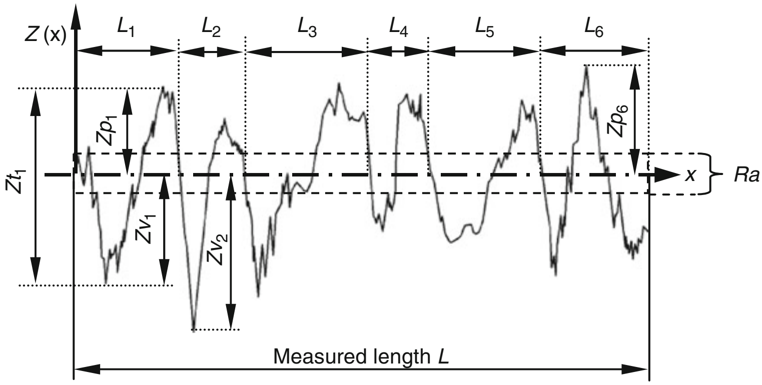


Fig. 2.26 Fundamental terms of surface inspection technology

the measured length L, which is used for evaluation ($L < L_t$) [Grot05]. The detected profile (actual profile) of a surface depends on the measuring procedure and the filter used, thus it only represents an approximate image of the actual surface. The reference profile shifted within the measured length perpendicularly to the geometrically ideal profile is defined as the middle profile. This is oriented in such a way that the surface areas above and below the middle profile line are equally large (Fig. 2.26).

By using different measuring procedures and depending on which filter is used, different profiles can be determined [DIN EN ISO 4287]. These are the P-Profile (primary profile), the R-Profile (roughness profile) and the W-Profile (waviness profile) (Fig. 2.27).

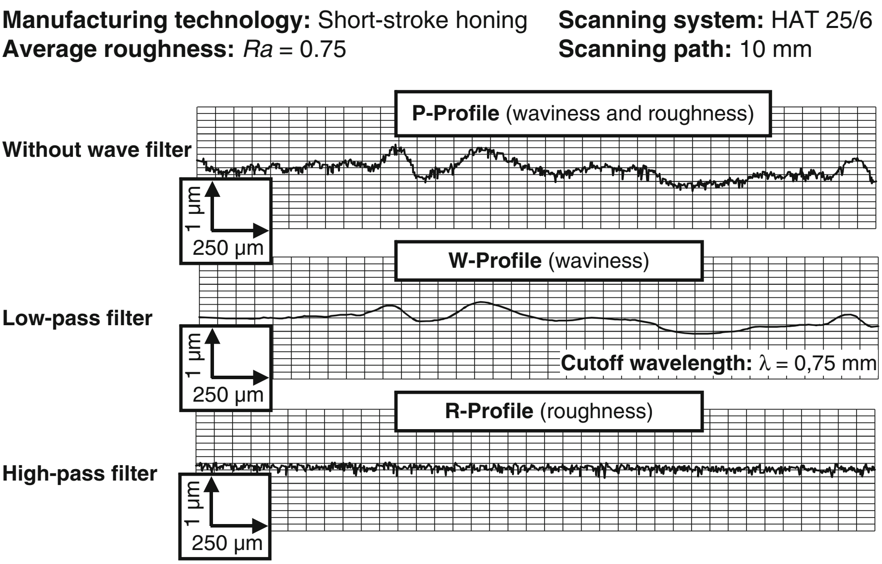


Fig. 2.27 Separation of waviness and roughness by wave filter

The examples given below refer to the R-Profile (roughness) (Fig. 2.26). According to DIN EN ISO 4287, the following roughness parameters can be distinguished:

- The height of the highest profile point R_p: value of the y-coordinate $Z(x)$ of the highest profile point of the middle profile line within the sampling length L_i.
- The depth of the deepest profile valley R_v: value of the y-coordinate $Z(x)$ of the deepest point of the profile of the middle profile line within the sampling length L_i.
- The total height of the profile R_t: the sum of the highest profile point and the depth of the deepest profile valley within the measured length L.
- The greatest height of the profile R_z: the sum of the height of the highest profile point R_p and the depth of the deepest profile valley R_v within a sampling length L_i.
- The mean roughness value R_a: the arithmetic mean of the values of the y-coordinates $Z(x)$ within a sampling length L_i.

$$R_a = \frac{1}{L} \int_0^L |Z(x)| \, dx \tag{2.1}$$

Horizontal parameters (distance parameters) are also designated as bearing lengths. They are determined by means of tangential sections. Forming a ratio of of the summed single bearing lengths and dividing by the measured length yields the relative bearing length (material ratio) in a specified section depth c. By creating sections at different depths c, the bearing ratio curve – also called the ABBOTT-FIRESTONE curve – can be determined (Fig. 2.28).

The bearing ratio of the roughness profile $R_m r(c)$ is calculated as follows:

$$R_m r(c) = \frac{\sum Xi}{L} \tag{2.2}$$

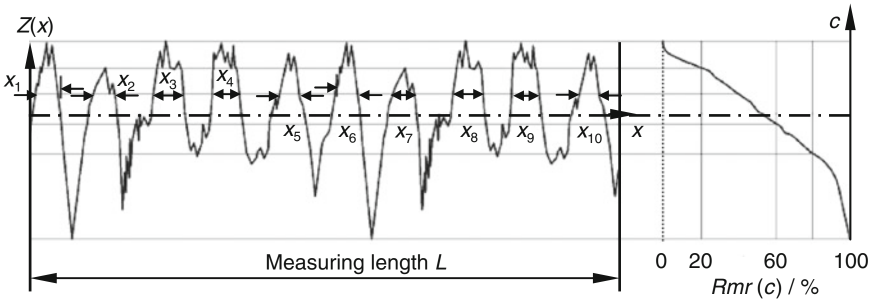


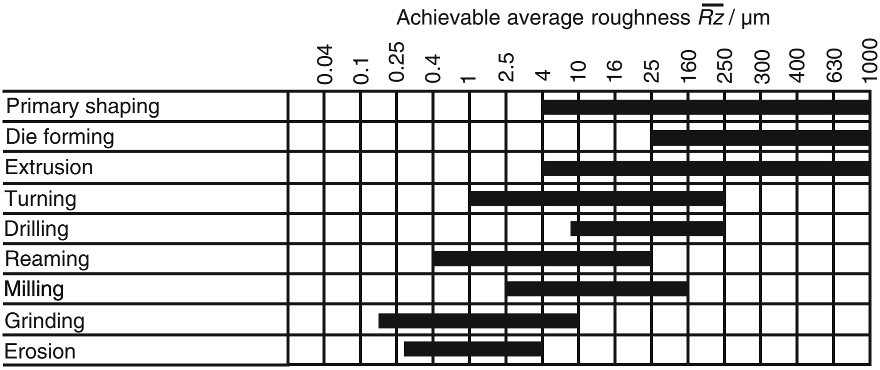
Fig. 2.28 Bearing ratio curve of the profile, acc. to DIN EN ISO 4287

The bearing ratio can be calculated on the basis of the primary profile (P_m), the roughness profile (R_m) and the waviness profile (W_m).

Using the average roughness, Table 2.2 provides an overview of the surface roughness values which can be achieved with different manufacturing processes.

With respect to general specifications on achievable surface values, one must consider the fact that it is not necessarily possible to deduce the manufacturing process when using one-dimensional parameters for describing the surface [Abou76]. Due to the characteristic engagement conditions between the workpiece and the tool one would also have to specify, for each surface parameter, which manufacturing process is to be used to create that parameter. This problem is somewhat alleviated if multiple one-dimensional surface parameters are used instead of just one when describing the manufactured surface or if surface reference standards are available (Figs. 2.29 and 2.30).

Table 2.2 Achievable average roughness



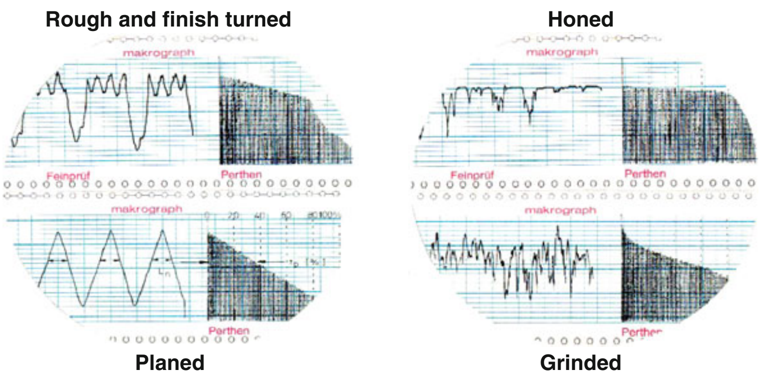


Fig. 2.29 Surface quality for several manufacturing operations

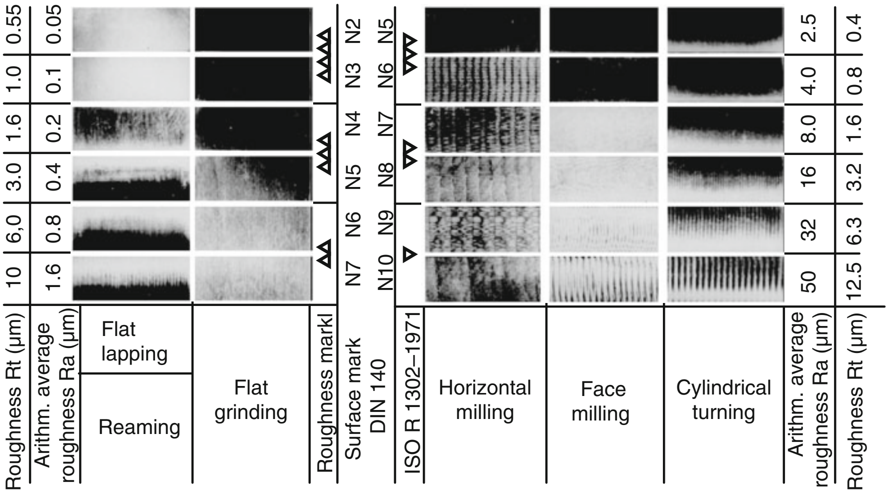


Fig. 2.30 Surface reference standard (Source: Rupert)

2.4.2 Subjective Surface Inspection

In some cases, a visual inspection can determine whether the processed surface meets the specified requirements. A testing device frequently used in the workshop is the straight edge, which is used to check the evenness of a surface using the light-slit method. In workshop operations, spotting straight edges or spotting plates are used to detect form deviations or contact patterns on the workpiece surface (Fig. 2.31).

Impression methods using lacquers have been developed for surfaces which are difficult to access (e.g. drill holes, internal surfaces). The lacquer is applied onto the

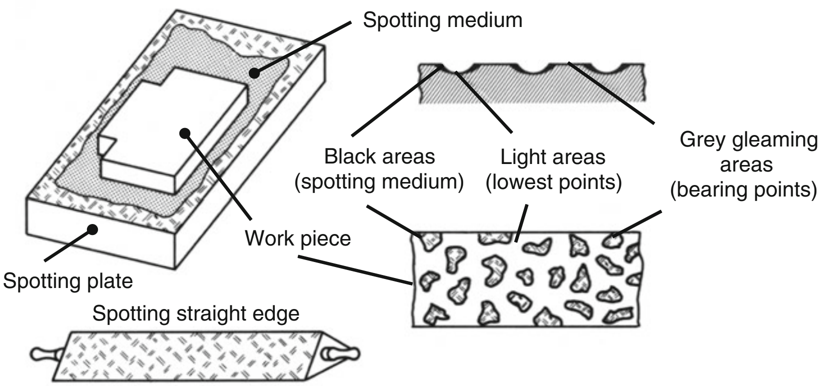


Fig. 2.31 Surface inspection by spotting

test surface and pulled off after drying. The contact patterns attained on the lacquer film thus attained can then be evaluated.

A frequent use of spotting is detecting contact patterns in quality testing and in the assembly of gear teeth (especially bevel gear teeth). Applying spotting paste and then rolling the teeth under light strain causes the bearing points on the tooth flanks to become visible. These bearing points can then be compared to the reference contact pattern. Nowadays in individual cases machine-tool guiding elements also become scraped, therefore, spotting is used to judge the surface.

2.4.3 Surface Measurement

All the physical principles mentioned in the context of length measurement technology are also fundamentally applicable to surface measurements. Since mechanical and optical measuring methods have proven to be the most effective in this field, the following discussion will limit itself to these methods.

2.4.3.1 Mechanical Measuring Methods

Devices for surface measurement which function on the basis of a mechanical functional principle are generally referred to as stylus instruments. Mechanical measuring methods are classified as either scanning methods or sensing methods. In the *scanning method*, a contact stylus descends upon the surface to be tested at a specified frequency. The surface is guided under the needle with a constant feed rate. The path of the contact stylus can be visualized mechanically, optically, electrically or electronically. The contact stylus can either be raised to a fixed level (the WOXEN principle) or raised by a fixed amount from the respective point of impact to the surface (differential tactile procedure) (Fig. 2.32).

In the differential tactile procedure, the impact energy of the contact stylus is lower in comparison to the WOXEN principle and exhibits marginal dispersion. As a result, the penetration depth of the needle remains constant, the measuring accuracy being thus higher than in the case of the WOXEN principle. In the case of instruments functioning according to the *sensing method*, the contact stylus is guided continuously over the surface. The needle rises and falls in line with the profile pattern

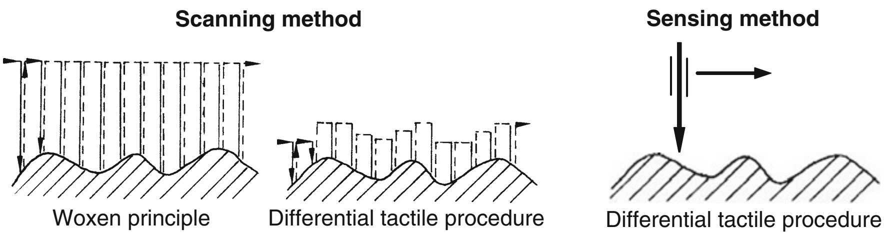


Fig. 2.32 Mechanical measuring methods

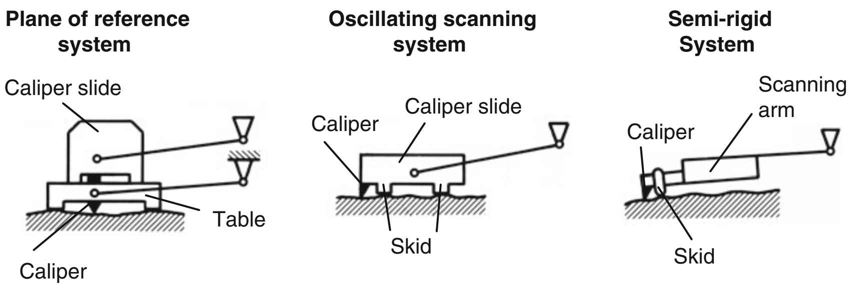


Fig. 2.33 Different surface scanning systems

(Fig. 2.32). The lifting motion is indicated relative to a reference point defined in the device or to a reference level. Here too, mechanical, electric, optical and electronic converters are used.

Sensing profile methods are the most widespread in practice. Independently of the design type of the contact stylus instruments used, three system designs are distinguished (Fig. 2.33).

Plane of Reference System

In this system, the scanning unit is guided on a reference surface (plane, cylinder) which corresponds to the ideally geometrical surface of the test sample and is oriented along the surface to be measured (Fig. 2.33). Aside from errors arising due to the calliper geometry, this scanning system provides a faithful transmission of the roughness and waviness values of the test sample. When measuring small or very large surfaces, however, the handling of this scanning system can frequently become unwieldy. An alternative is the reference surface contact system. Here, the workpiece is conveyed on very precisely guided slides in a horizontal direction beneath the firmly anchored scanning system. Besides roughness, the macrostructure of a surface can also be detected in certain areas.

Semi-Rigid System

In semi-rigid systems, the scanning unit, which contains the contact stylus, is guided on the skid gliding on the surface to be measured (Fig. 2.33). This system has the advantage that it requires little space and is thus suitable for measuring small or hard-to-access surfaces. A disadvantage is that the system requires an orientation to the surface to be measured which can cause parts of the profile to be transmitted in a distorted manner.

Oscillating Scanning System

Two glide skids guide the scanning unit of the oscillating scanning system (Fig. 2.33). The latter is oriented towards the surface to be measured and is thus comfortable to operate. However, it requires more space than the single skid system and can therefore not be used for small or hard-to-access surfaces. The distortions caused by long-wave profile sections are smaller than those in half-rigid systems, because the skids are flat and farther apart. Nevertheless the waviness must be filtered out in many cases [Henz68].

Usually, the magnification gauges for *x*- and *y*-coordinates are selected in a highly varying way in profile records. This is necessary because the measuring lengths (abscissa) lie in the mm region and roughness parameters are represented on the ordinate which lie in the μm region. The optical impression of the profile record is thus strongly distorted in comparison to reality. The contact styluses used in contact stylus instruments often have an apex radius of 2 μm. They function with a bearing strength of 0.5 N, which can result in considerable surface pressures (up to 6000 N/mm^2), which possibly cause alteration of the test surface. On the other hand, excessively large contact stylus radii distort the result; they act like mechanical filters. Thus the optimal conditions must be determined on the basis of the material of the test sample and documented in their entirety in the measurement report.

2.4.3.2 Optical Measuring Methods

White-Light Interferometer

This technology differs from length measuring technology both in that it employs white light, i.e. light with the entire wavelength spectrum, and in that it does not just use one beam, as with laser interferometers, but rather an entire bundle. A reflected-light microscope is used to display an image of a section of the test object on a detector (e.g. CCD camera). By using different interference lenses, a beam splitter can be used to superimpose a highly accurate reference surface with the image of the test object on the same scale. The interferences which are then created can be detected and evaluated (Fig. 2.34).

The topography of the test object creates a spatial modulation of the light intensity in the interference image. Depending on the surface to be measured, two different measuring modes are used: one to characterize very flat surfaces with an average roughness value R_a < 1 nm and one for all other surfaces. Steps and roughnesses of up to several millimetres high can be displayed using this technology.

Fringe Projection

The fringe projection method functions according to the triangulation procedure, in which equidistant stripe patterns are observed and evaluated at a certain angle, i.e. the triangulation angle. The stripe patterns on the test object are detected and evaluated from a certain position, with the projected stripes following the arbitrary form of the test surface. These stripes appear from the observer's standpoint to be "interferences", though they only appear this way because the location of the projection

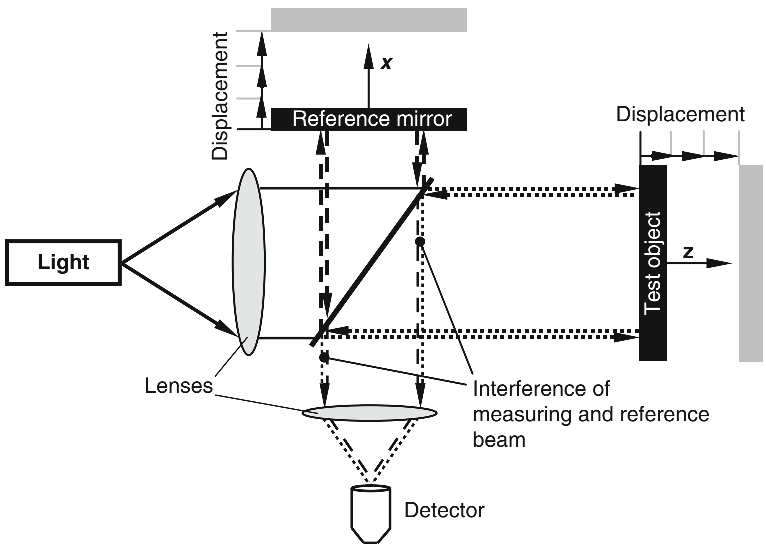


Fig. 2.34 Principle of a white-light interferometer (two-beam interferometer)

surface points varies in relation to that of the projector. The stripe patterns then are evaluated interferometrically on the basis of fluctuations in light intensity. The most important geometrical values on which this method is based are:

- the real distance of the projected stripes
- the stripe distance registered from the position of observation
- the triangulation angle

Fringe projection is used, for example, to judge surfaces bent over a large area, such as those found in deep-drawing tools and on deep-drawn parts. The advantages of this method are a high measurement speed and a spatial or laminar scanning. A disadvantage is that the test objects may not be transparent or reflective.

2.5 Inspection of the Workpiece Rim

The functional behaviour and applicability of a component depend not only on its macrogeometry and surface roughness, but also from the physical properties of the material both on the interior and near the surface. While the inspection of material properties properly belongs to the field of materials science and materials testing and thus cannot be treated here in further detail, the following will discuss some of the properties of technical surfaces and of layers near the surface (i.e. the rim zone) and methods used to measure rim zone properties. Technical surfaces can be categorized according to types of load into the following groups:

- external surfaces of technical products of all types, i.e. visible surfaces, covering surfaces, indicating surfaces, etc. They are generally mechanically unstrained, but are exposed to climatic or environmental stresses.
- surfaces subjected to heat, radiation or electrical currents, such as insulating surfaces, electrical contacts, or the like. Such surfaces are referred to as thermally stressed, radiation stressed or electrically stressed surfaces.
- surfaces which come into contact with fluids or gases. On the one hand, a corrosive stress may be predominant, or a flow stress with cavitation and erosion processes may occur in the case of flowing media. Also, surface boundary currents may be influenced via microstructures (ribblets).
- surfaces in mechanical contact with moved counter bodies. This strain is referred to as tribological stress. These stresses are found, for example, in typical machine elements, such as bearings, couplings, brakes, gear-teeth, etc. With this type of stress, different kinds of wear may occur.
- optical surfaces used to form and conduct electromagnetic waves. Optical surfaces are produced with mirrors and transparent components. The basic beam-conducting and forming principles are reflection, refraction and diffraction.
- biologically stressed surfaces exposed to the effect of microorganisms.

2.5.1 Surface Layers

The properties of technical surfaces relevant to component behaviour are determined through the entirety of the physical and chemical properties of the surface layer. These properties include textural structure, hardness, strength and residual stresses in the rim zone near the surface. The surface rim zones of technical bodies are created through machining processes. A part of the energy used to create the surface always flows into the workpiece and is either stored or causes change processes in the base material. Thus every machining process also causes a change of the surface rim zone vis-à-vis the base material. Whether these changes affect the functionality of the workpiece must be tested and confirmed in individual cases. The distinction is frequently made between the external and the internal boundary layer. Figure 2.35 shows the structure of both boundary layers.

The layers referred to here cannot be clearly defined; there are no fixed boundaries between them.

For further reference, please refer to the following sources: [Schm36, Schl51, Czic03].

2.5.1.1 The External Boundary Layer

The external boundary layer is located between the surrounding atmosphere and the atoms of the base material embedded in the crystal lattice. It is generated via the reaction between the material and the atmosphere during and after machining. The external boundary layer encompasses the following individual layers:

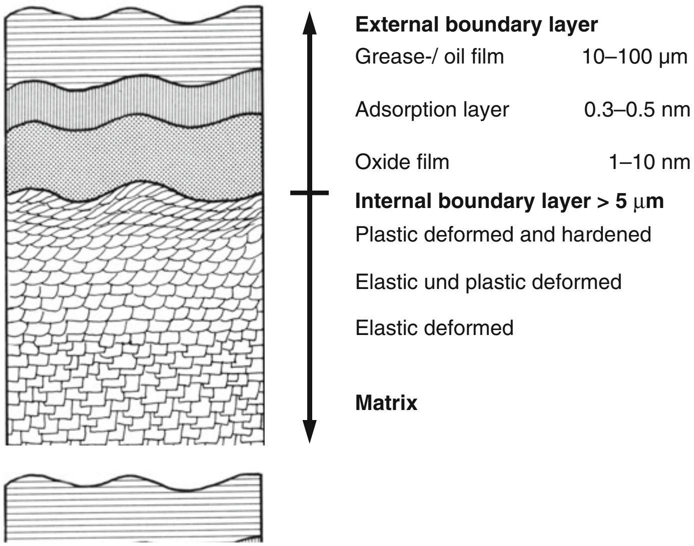


Fig. 2.35 Layer structure of metallic surfaces, acc. to SCHMALTZ [Schm36]

Reaction Layers/Oxide Film

On the surface of metals which are either freshly machined or created through breakage can form thin reaction layers/oxide films. These layers may only have a thickness of 10–20 molecular layers. They may, for example, influence wetting capability or adhesive behaviour.

Adsorption Layer

After a short duration of time of being exposed to the air, the oxide layer is covered with an adsorbed layer of water and gas. This adsorption layer becomes considerably important, for example, in the context of electrical resistance when metallic contacts are present.

Grease/Oil Film

Coolants in particular cause a grease and oil film to deposit itself after machining on the adsorption layer. This film ranges from 10 μm to several 100 μm in thickness. A grease and oil film can still be detected even after cleansing. These films can exert considerable influence interface formation in further galvanic, adhesion, or PVD/CVD processing.

2.5.1.2 The Internal Boundary Layer

The internal boundary layer is the layer of the machined workpiece bordering on the base material and thus possesses practically the same chemical composition as the

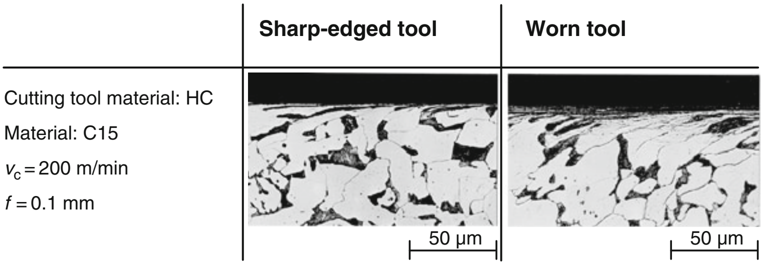


Fig. 2.36 Plastic deformation of the workpiece rim by drilling

base material. The physical structure and the expansion of this layer in the direction of the workpiece interior depend both on the material used and the manufacturing operation used. The transition from the affected rim structure to the unaffected base structure is continuous.

Figure 2.36 shows a model of the plastic deformation of the structure of case-hardened steel C15 after a drilling operation. Larger mechanical and thermal stresses caused by worn tools lead to clear modifications of the textural structure.

In steel material processing, for example, given high enough temperatures and high cooling rates, a hardening zone may develop in the outermost surface layer. In the layers below this, annealing processes are possible due to the lower temperatures and cooling rates in these layers (Fig. 2.37). As shown in Fig. 2.37, a hardening zone has developed which has an extremely negative effect on the flank bearing strength.

2.5.2 Inspection of the Surface Rim Zone

Since, in addition to surface geometry, the physical properties of the areas near the surface play an essential role, these properties must be tested, too. Therefore methods familiar in the field of materials testing are applied:

- material analysis
- structure and texture investigation
- hardness testing
- fracture mechanical testing
- residual stress measurement

Structural changes caused by increased thermal stresses of the rim zones near the surface can be determined in structure and texture investigations which are standardly used in materials science. This is done by metallographic preparations.

Crack detection in rim zones of workpieces can be either destructive or non-destructive. A crack is a locally limited detachment of the material structure of small width but often considerable length and depth. The crack can arise through internal

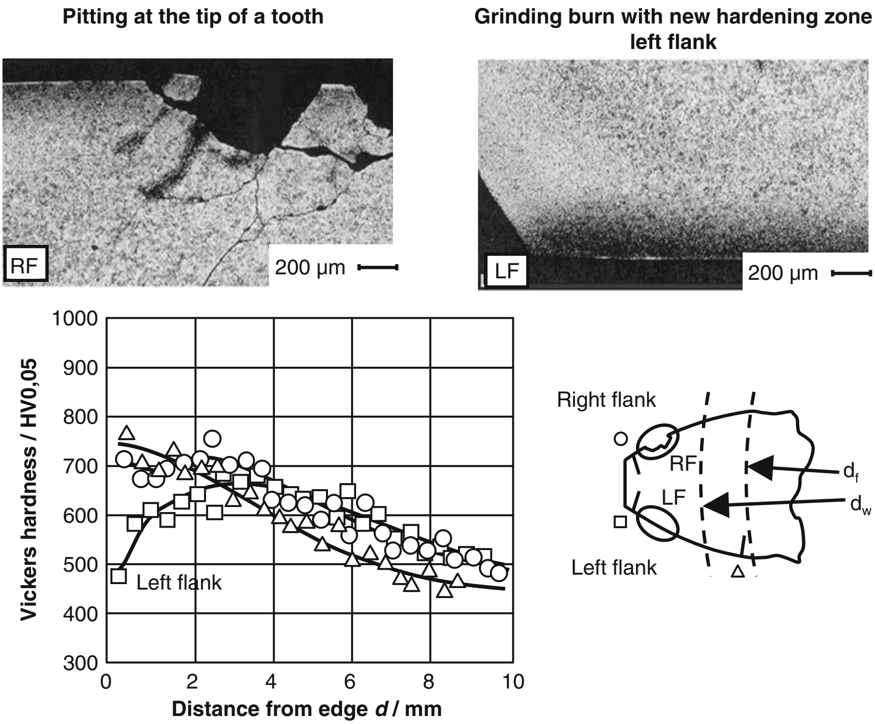


Fig. 2.37 Grinding burn during gear tooth grinding

tensions or through external force effects. For further reference, please refer to the specified literature [Schu04].

2.5.2.1 Residual Stresses

Residual stresses are characteristic for the internal tension of a load-free workpiece. This tension results from inhomogeneous elastic and elastic-plastic deformations which are present without the influence of external forces and torques. For every component, there is a balance of all the internal forces and torques created by residual stress. Residual stresses are subdivided into macro-residual stresses (type 1) and micro-residual stresses (types 2 and 3). Residual stresses caused by mechanical and thermal influences is treated in the chapters devoted to the relevant manufacturing operations. The basic formation mechanisms of thermally and mechanically induced residual stress are shown in Fig. 2.38.

Residual stresses become significant in the context of dynamic stresses. The attempt is therefore often made to use manufacturing processes in finishing which create compressive residual stresses in the surface rim zone in order to minimize the probability of crack formation and crack growth. Such operations include, for

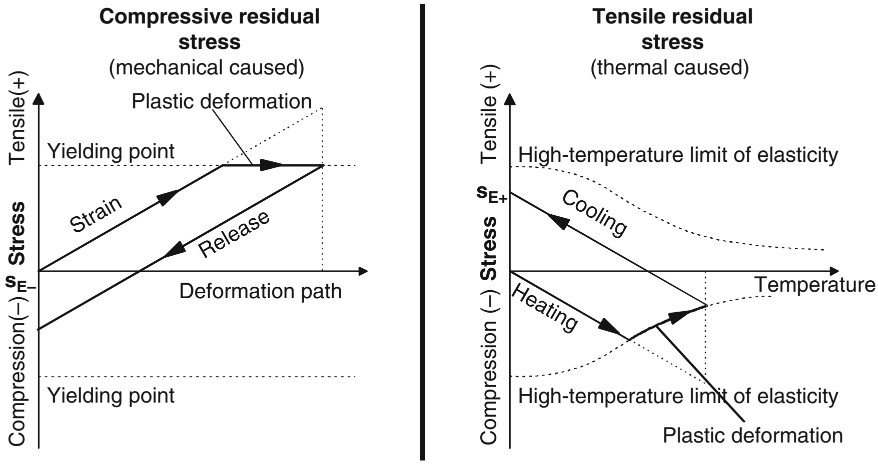


Fig. 2.38 Formation of residual stress

example, finish and surface rolling as well as shot peening. In contrast, tensile residual stress is probable in electrical discharge machining, because of its thermal operating principle; in grinding and all manufacturing operations which use geometrically defined cutting edges, both mechanical and thermal load spectrums occur during processing, a prediction of the stress state is not easily possible.

Methods of Analysis

For all processes, the metrological definition of residual stresses occur indirectly through the measurement of strains, electromagnetic parameters or speed of sound. Below, the basic methods used in manufacturing technology will be explained. For further information on this topic, please refer to the specified sources [Peit92, Hauk87].

Mechanical Methods

The mechanical methods of analysis include the borehole method and the toroidal core method. These are destructive methods which release residual stresses in the rim zone near the surface through the insertion of very small holes or ring grooves in this zone, which causes an altered stress state and thus strains, which can be measured with wire strain gauges, for example. The average residual surface tension can then be calculated from the strains in consideration of the material behaviour.

By removing layers of the surface rim zone at different surface positions, distributions of residual stresses can be defined up to the depth corresponding to the drill's diameter. Since drilling or milling processes only cause reproducible strain changes at a depth of several hundredths of millimetres, this method cannot be used to determine residual surface stress with strong rim zone gradients.

X-ray and Neutron Diffraction

In research and practice methods are used which utilize the diffraction of monochromatic X- or neutron radiation on the crystalline lattice structure of the material phases (Fig. 2.39).

The BRAGG condition applies here:

$$n \cdot \lambda = 2 \cdot a \cdot \sin \Theta \tag{2.3}$$

Altered lattice distances a of the material phases can be calculated very accurately from the displacement of the diffraction lines, which in turn allow to draw conclusions about residual stresses. The chosen measuring direction defines the stress components to be detected. This allows the definition of the entire stress tensor by measuring in multiple directions. In order to calculate residual stresses from strain measurements, the elastic properties of the material phases are used. In the case of many materials, their anisotropic behaviour can even be taken into consideration when measuring at the respective lattice levels. Figure 2.40 shows the customary device for measuring residual stresses (goniometer).

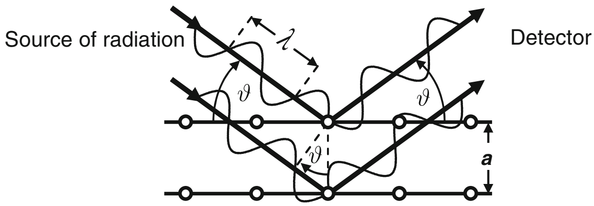


Fig. 2.39 Principle of X-ray diffraction on crystalline lattice

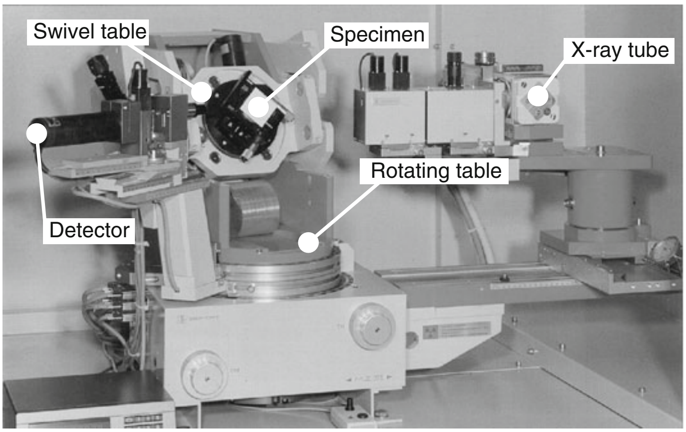


Fig. 2.40 Goniometer

Diffraction methods demand high requirements on measurement technology and on occupational safety (radiation protection). X-ray diffraction is used in practice to define residual stresses. In research, neutron sources can also be accessed at selected locations, with which it is possible to detect depth structures up to some millimeters without removing surface layers.

The X-ray method has a depth of penetration which is limited to an extent depending on the absorption properties of the material and the wavelength used for the X-radiation. Given the usual measuring parameters, the average penetration depths vary between approximately 1 μm for tungsten carbide and 5 μm for steel; significantly greater depths of penetration are possible for light metals. Residual stress depth profiles with great rim depths can be produced through the electrochemical removal of layers of the surface rim zone.

Magnetic Methods

Magnetic analysis methods use the influence of mechanical stresses on resetting in ferromagnetic materials. These changes can be measured by means of an externally applied alternating magnetic field. The measurands are coercive field strength, superposition permeability, dynamic magnetostriction and magnetic and acoustic BARKHAUSEN noise. The simultaneous analysis of several magnetic parameters improves the evaluation of the quantitative measuring data. Magnetic methods are characterized by compact and easily manageable test set-ups. Depending on the material and the range of frequencies analyzed, surface rim zones can be gauged ranging from a few micrometers to over 1 mm. Disadvantegous is that these methods they are limited to ferromagnetic materials and have to be calibrated to known material states.

Acoustic Methods

Residual stresses are generated through lattice strains of the material which result in an altered propagation of structure-borne sound. This acoustic-elastic effect can be used to analyze stresses by means of ultrasonic measurements. Such methods are based on the assumption that the sound velocity is proportional to the lattice strain. The applicational potential of these methods are limited above all by the material state. This is because microstructural errors and textures exert as great an influence on sound velocity as structural gradients.