# Chapter 1
# Measurement and Test Techniques

E. Abele, J. C. Aurich, B.-A. Behrens, D. Biermann, C. Brecher, E. Brinksmeier, M. Czora, B. Denkena, U. Engel, K. Großmann, U. Heisel, D. Heinisch, R. Hermes, B. Kirsch, F. Klocke, A. Krause, T. Kroiß, R. Laurischkat, M. Löser, F. Mahr, H. Meier, M. Pischan, P. Rasper, A. V. Scheidler, M. Storchak, E. Uhlmann, and M. Weiß

**Abstract.** Nowadays, different measurement and test techniques are used to investigate the interaction between processes and machine tool structures. Machine and workpiece properties are determined after analyzing the individual factors of process metrology, which have an effect on the process. This chapter explains the measurement methods for the structural analysis of the machine tool as well as for manufacturing processes and for the workpiece analysis. In addition, an overview of different measurement and test techniques based on selected examples related to the priority program 1180 is given.

## 1.1 Introduction

This chapter analyzes the metrological possibilities in order to determine the interaction between process and machine structure. The metrological analysis is subdivided into three main sections: Section 1.2 refers to the structural analysis of the machine tool, section 1.3 to the process analysis and section 1.4 to the analysis of the workpiece. In section 1.2 different measurement and test techniques of the static and the dynamic machine tool behavior, the kinematics and the temperature of machine tools are described. Section 1.3 describes different measurements and test techniques for force, acoustic emission and temperature, whereas section 1.4 describes refuse to surface and geometry assessment. Here, a small imported outline can be obtained and its influence must be analyzed to understand the interaction between process and machine tool structure for specific examples.

## 1.2 Structural Analysis of Machine Tools

Working precision, performance, environmental behavior and reliability of machine tools affect the quality of manufactured products and the efficiency of the processes significantly. Technological progress in the machine tool industry and the competition pressure to increase productivity ask for higher performance, higher spindle speeds, higher feed rates and longer material removal rates. Hence, new and optimized machine tool structures have to be developed. In addition, due

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to significantly increased process loads the demands concerning the working accuracy of the machine tool have increased as well. Thus, apart from performance values like spindle power and speed or feed rate the structural and mechanical properties of the machine tool have to be known in order to assess the accuracy and productivity [1].

To analyze and improve the machine tool behavior it is essential to describe the machine tool characteristics by defined parameters. Despite the good progress in calculating machine tool parameters, the experimental determination of the structural properties is still essential for the parameterization and evaluation of machine tool models. The accuracy of machine tools is primarily affected by deviations at the tool-workpiece interface. Depending on the transmission behavior of the machine tool thermal, static or dynamic loads result in kinematic and geometric deviations from the desired working motions. Therefore, the thermal and dynamic behavior limits the theoretical performance of the machine tool. Due to dynamic instabilities and displacements caused by thermal dilatation the full potential of machines cannot be exploited, which results in a negative impact on the productivity. To ensure the efficiency of machine tools the interactions between process and structure have to be determined. In the following sections, different measurement methods for the analysis of the static, dynamic and thermal structure, their behavior as well as the kinematics are described.

### *1.2.1 Static Machine Tool Behavior*

Static process forces between the workpiece and the tool lead to a static stress on all components and joints of the machine structure included in the flow of force. Thus, the stiffness properties of the machine are the sum of the individual stiffnesses of the concerned elements. The influence of the machine properties on the workpiece is usually of particular interest; hence, investigations of the machine tools stiffness focus on the interface between tool and workpiece. Therefore, the relative displacement between the tool and the workpiece as a result of static process loads has to be investigated. While the process load is usually applied in the three Cartesian coordinate directions, the measured displacements are divided into tilts and deflections. These are each described by a translational and a tilting stiffness matrix, in which the main stiffnesses are located at the principal diagonal of the matrix with the cross stiffnesses next to them. Figure 1.1 shows an example of the analysis of the main stiffness in the z-direction and the tilting about the x-axis by applying a load in z-direction. Machine structures usually show a progressive development of stiffness. After overcoming the clearances in the bearings, the guidance and the screw connections as well as the internal friction in the gears and seals, the stiffness rises with increasing load. Changing contact conditions and internal friction in the joints and contact points cause a hysteresis between loading and load relieving. In this section, the determination of the static stiffness is explained by a press and an industrial robot.

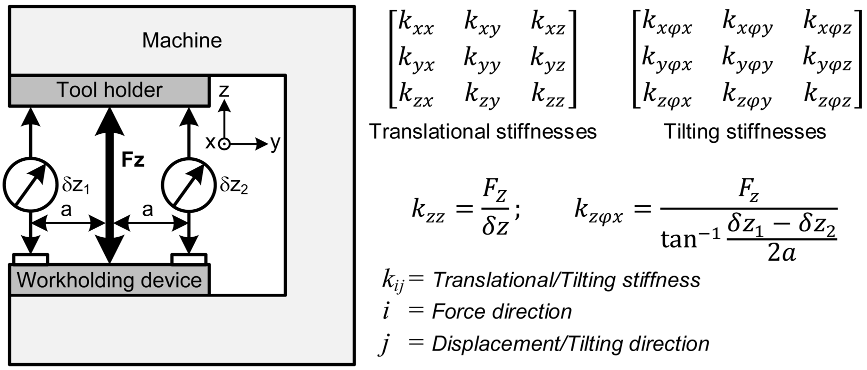


**Fig. 1.1** Characterization of static machine compliance (based on [1])

A method to determine the deflection of presses under a static load is described in the standard DIN 55189 “Determination of the ratings of presses for sheet metal working under static load“ for mechanical presses (part 1), as well as for hydraulic presses (part 2) [2]. By means of this method the press is loaded by a hydraulic system, which is applied torque-free by means of a compensation device in z-direction (Fig. 1.2).

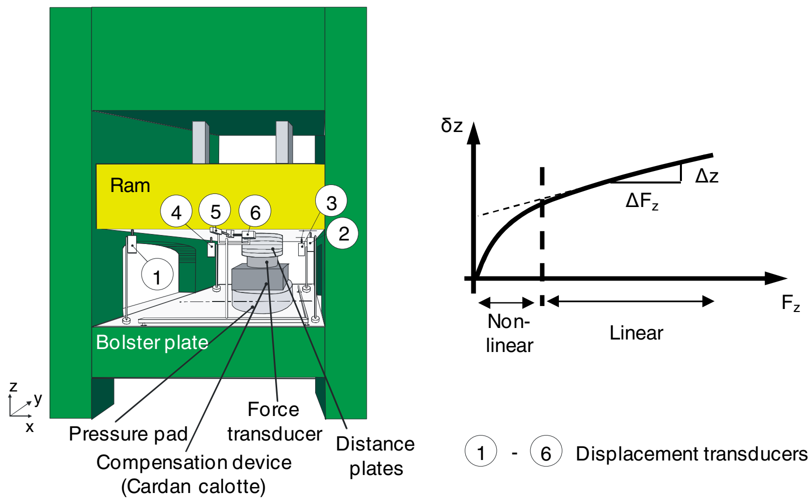


**Fig. 1.2** Measurement setup according to the DIN 55189 and resulting displacement development

The standard describes the determination of the deflection in forming direction caused by a centric load and the tilting of the ram as well as its horizontal displacement by an eccentric load. The investigated force-displacement characteristic can be classified into two periods, an initial non-linear displacement and tilting period, which occurs due to bearing clearances, and a period during which the press deflects linear elastically. The relevant static press characteristics such as the horizontal displacement, the tiltings about the x- and y-axis and the stiffnesses, are also defined in DIN 55189 and can be determined by the recorded force-displacement and force-tilting characteristics. The static press characteristics make it possible to compare different types of presses with each other.

In the following paragraph, the determination of the static stiffness of an articulated robot is shown. In Figure 1.3, the measurement setup as well as a typical stiffness in the working space is presented.

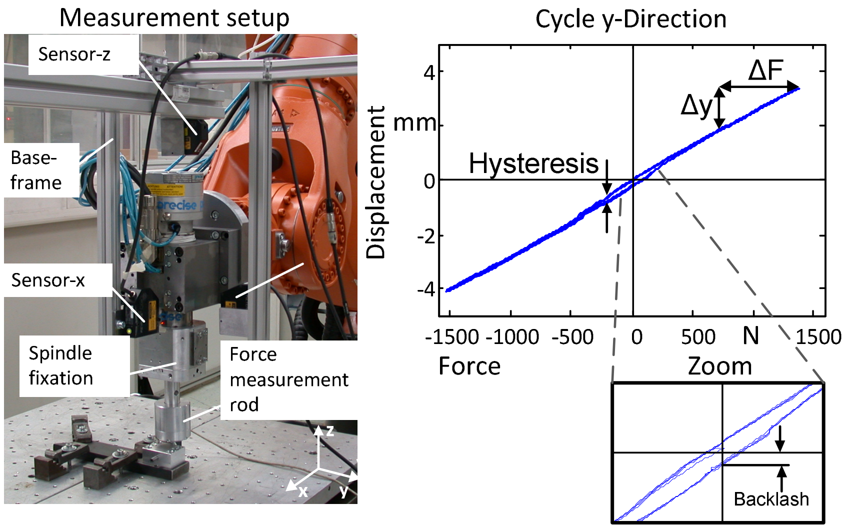


**Fig. 1.3** Experimental setup (left) and typical results (right) of an articulated robot

The setup consists of a force measurement rod to apply and detect tensile and compressive forces and laser distance sensors to measure the displacement of the robot due to the force. The difference in the tensile and compressive cycles indicates hysteresis. The backlash amounts to approximately 0.2 mm at the measurement point x = 1,900 mm, y = 0 mm and z = 600 mm in the base coordinate system. Furthermore the measured curves show a slight s-shape due to a non-linear structural behavior. Using the least-squares method a linear slope can be fitted into the measured curve. The gradient of the measured curve then indicates the stiffness.

### *1.2.2 Dynamic Machine Tool Behavior*

The accuracy of a machine tool is determined by the deflection occurring at the contact point between tool and workpiece at the specified target position. Apart from the influences of the static loads, which are described in the previous chapter, the dynamic behavior under varying loads is also a criterion for the performance of a machine tool system. Unbalanced dynamic properties of this system lead to oscillation phenomena, which can result in a poor surface quality of the workpiece, increased machine and tool wear, tool breakage and damage of the machine tool. The latter mentioned damages have to be considered particularly with regard to the occurrence of regenerative chatter oscillations, which increase as a result of the interactions between the dynamic machine tool behavior and process behavior during the machining process [1], [4].

Therefore, the aim of investigating the dynamic machine behavior is to describe possible weak points of the mechanical structure quantitatively using the tools of frequency response measurement and experimental modal analysis [40]. A major application of modal analysis in mechanical engineering is trouble-shooting. As an example, chatter vibrations in machine tools are often caused by structural instabilities, which can be identified using experimental modal analysis techniques. Recently, the investigation of the dynamic machine tool behavior has become more important for the configuration and alignment of simulation models. Nowadays, an important application is the correlation of finite element models with experimental data from modal analysis in order to improve the accuracy of structural dynamic simulations. This is very useful for sensitivity analyses and the prediction of the dynamic behavior due to structural modifications.

The investigation of the dynamic machine tool behavior is always based on the measurement of the frequency-dependent rigidity of the structure [3], [4]. Among signal processing and analog digital conversion (ADC), the required measurement chain can be divided into three major systems. The first is the excitation of the structure. This can be done in several ways. The most commonly used are an attached shaker or a hammer blow. Electromagnetic or electrohydraulic shakers are controlled by a signal generator providing the ability to induce various loads into the structure. These loads can be, for example, sinusoidal, periodic, random or transient. Especially sinusoidal loads, such as sine sweep or stepped sine, are preferably used to investigate non-linear system behavior by analyzing the structure with varying load amplitudes. However, the use of a shaker requires a connection to the structure, which remains attached throughout the test. This makes shaker testing less flexible for in-the-field testing. In contrast, hammer testing provides the advantage of inducing the excitation force in a contactless way. As the hammer impact excites the structure over a wide frequency band, hammer testing is a very fast and convenient way to determine the compliance behavior of a machine tool. Since manipulation of the frequency content and amplitude of the compact is limited, it is less appropriate for analyzing non-linear system behavior. [6]

The second subsystem of the measurement chain provides the detection of the loads, which are induced into the machine tool structure. Therefore, piezoelectric crystals or strain gauges are used, which are integrated into the force flux between the machine tool structure and the exciter. The third subsystem consists of the measurement technique for detecting the vibration response of the machine tool structure. In addition to systems for direct measurement of the displacement, e.g. inductive transducers or optical measurement techniques piezoelectric accelerometers are used as well.

### 1.2.2.1 Frequency Response Function

The frequency response functions (FRF) represent the dynamic compliance behavior of a machine tool structure in frequency domain. Also, process stability and the occurrence of forced vibrations can be assessed on the basis of these measurement data.

For the determination of the frequency response function Fast-Fourier-Transformation-analyzers (FFT) are used. Therefore, the analog force and deflection/acceleration signals are sampled and digitalized. The sample rate determines the frequency range and the number of samples defines the frequency resolution of the analysis. To suppress high frequency disturbances analog force and deflection signals must be filtered before the digitalization.

The sampled time signals can be weighted by a so-called window function to avoid errors, which may occur when the signals are transformed into frequency domain. The type of window function depends on the signal that has to be analyzed. Commonly used functions are transient window (impact force), exponential window (response to an impact) and Hanning window. The transformation of the weighted signals into frequency domain is carried out by a discrete Fourier Transformation. The result of the transformation is a complex frequency spectrum, which can be depicted either as real part and imaginary part, magnitude and phase or as a Nyquist plot (Fig. 1.4). Separately from the depiction FRF describes the frequency-dependent deflection answer of a mechanical system regarding the dynamic load acting on it.

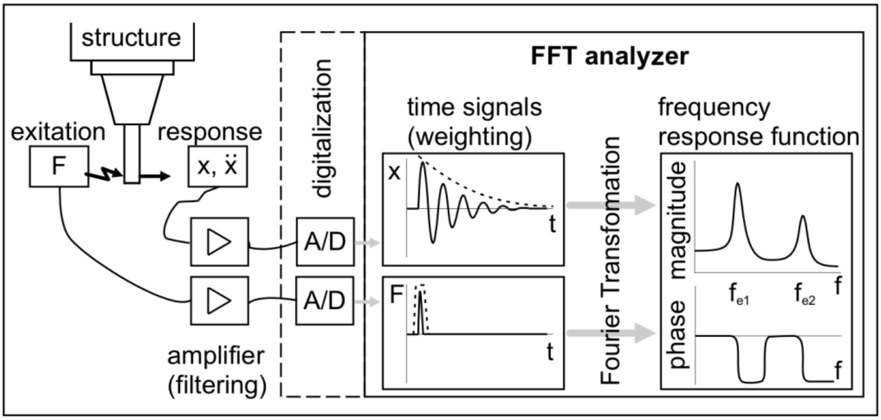


**Fig. 1.4** Principle of the measurement of frequency response functions

#### 1.2.2.2 Experimental Modal Analysis

Experimental modal analysis is a method for determining the dynamic characteristics of a structural system: its natural frequencies, mode shapes and damping factors. With these characteristics a mathematical model of the dynamic behavior of the system, a so called “modal model”, can be formulated [5], [6]. The vibration of a linear time-invariant system can be described by a linear combination of its mode shapes, which are inherent to the dynamic system and determined by its physical properties (mass, stiffness and damping) and their spatial distributions. Coming from an analytical model, the system may be given in forms of partial differential equations and their solution provides the natural frequencies and mode shapes [7]. A more realistic physical model usually comprises mass, damping and stiffness matrices, which characterize the system properties. By solving the eigenvalue problem the modal data can be obtained. Utilizing finite element analysis almost every structure can be discretized into differential equations of motion and hence permits theoretical modal analysis.

Experimental modal analysis is a technique used to determine the modal model of a linear time-invariant system. By measuring the vibration response at one or more locations and the excitation force at the same or a different location and calculating their ratio several FRFs can be obtained. From these FRF-measurements a modal model of the mechanical system can be derived. In order to obtain an accurate

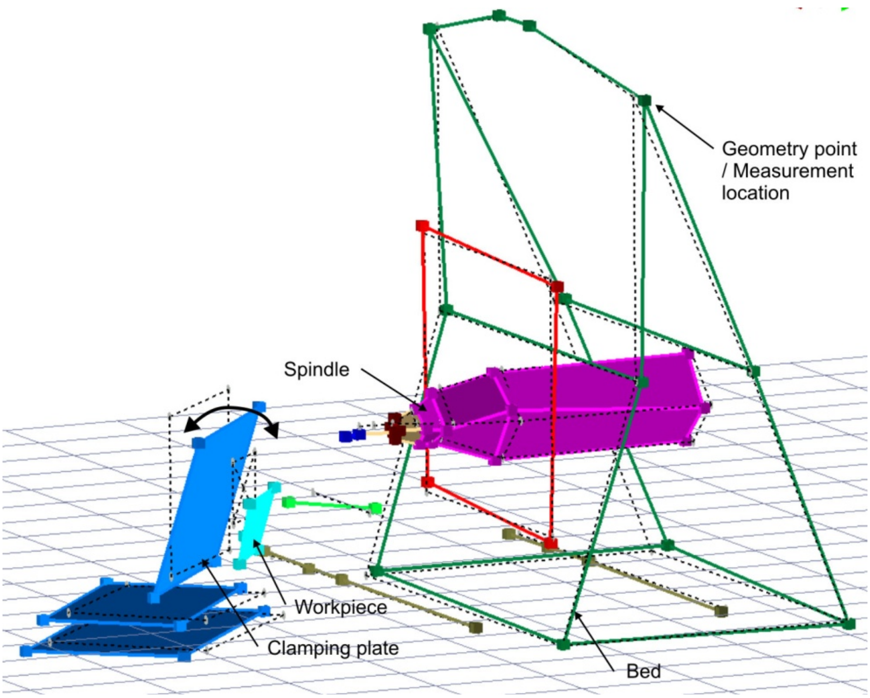


**Fig. 1.5** Geometry model with measurement locations of a horizontal milling machine

modal model of the examined system the proper selection of excitation and response locations is of particular importance. The mathematical models obtained from modal analysis can also be used for the prediction of structure responses due to exciting forces or for substructure coupling when a simple dynamic representation is more suitable than a complex finite element model.

Figure 1.5 shows a geometric model of a horizontal milling machine. Each geometry point represents a measurement location in the machine tool. The structure was excited with an impulse hammer at several locations and the vibration response was measured using tri-axial acceleration sensors. The obtained modal model can be used, for example, to predict chatter vibrations or to identify structural instabilities.

## *1.2.3 Measurement of Kinematics*

The accuracy of machine tools depends on a large variety of different influences. Geometric deviations in dimension of machined and formed workpieces can, according to [1], result in:

- Deviation of tool dimensions out of tolerances due to insufficient tool manufacturing
- Process-induced deviations such as tool wear or built-up edges
- Elastic deformation of the tool, the workpiece, clamping and support structures
- Deviations of the tool path regarding relative movement between tools and workpieces including force-induced deviations of the machine tool structure

Depending on the process the listed influences need to be considered when modeling the process machine interaction. A lot of different methods are available to measure the accuracy of the translational and rotational axes of machine tools. The spectrum reaches from simple measuring setups with test gauges, measuring straightness, parallelism, perpendicularity and concentricity up to complex and highly accurate methods. Some of these methods are described below.

### 1.2.3.1 Circularity Test

The circularity test allows the determination of the accuracy of a circular path, interpolated by a computer control unit. The deviations and vibrations can be traced back to the control unit, the drives and the machine kinematics. The test can be conducted using a double-ball-bar or a grid encoder. In the case of a grid encoder a photoelectric sensor moves over a plate, which contains a very precise measuring grid without contact. Using a double-ball-bar the circularity of the machine tool is determined by a position-measuring system. The system is integrated in the gauge. Performing the test with large radii gives information about the machine geometry, whereas small radii are used for the evaluation of the feed drive dynamics [1]. Afterwards, the measured path can be compared with the desired path. Figure 1.6 presents the measuring setup with a grid encoder (left) and a double-ball-bar (right).

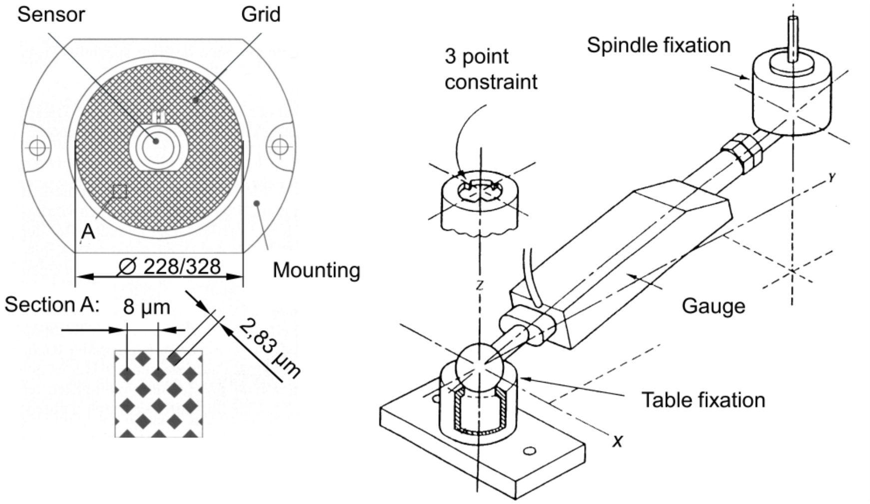


**Fig. 1.6** Measuring setup for the ball-bar test with a grid encoder (left) and a double-ball-bar (right) [1]

### 1.2.3.2 Back-Step Test

During the back-step test several positions are approached from both sides. This is repeated for each axis. The current position is detected by an external measuring system at the tool-center-point (e. g. a grid encoder or a laser interferometer) and is compared with the desired position. According to the VDI/DGQ 3441 standard the parameters positional tolerance, positional deviation, reversal error, positioning scatter band and position uncertainty can be determined from the measurement data (see Fig. 1.7).

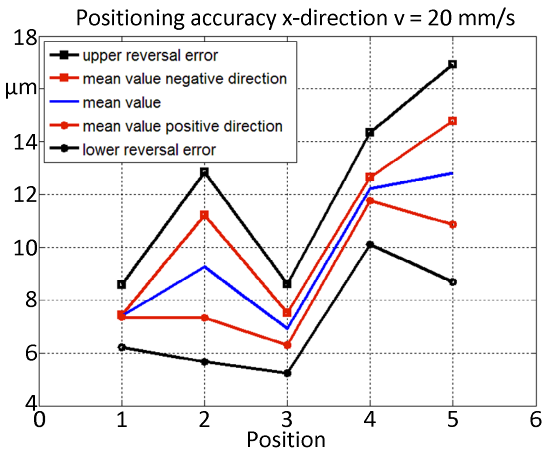


**Fig. 1.7** Procedure of the back step method (left); characteristic diagram and determined parameters (right)

#### 1.2.3.3 Measurement of the Machine Axes using Laser Interferometry

An approach for the determination of the kinematics of a machine tool is the measurement of the procedure movement of the machine axes. The measurement of the procedure axis is briefly described on the basis of a face grinding machine (Geibel & Hotz FS 635-Z CNC). The temporal response of the machine control was examined for the input of a correcting variable. The velocity and the acceleration of the machine table were measured. A laser interferometer system with a scanning rate of $f_a = 20$ Hz was used in order to avoid the influence of machine vibrations on the velocity and acceleration measurements. The change of movement between the interferometer and the retro reflector was measured with evaluation software. [8]

For the investigations the strokes were measured by several sequential starting points with constant, well-defined point distances at different workpiece velocities. The dependency of the workpiece velocity on the selected step size is shown in Figure 1.8.

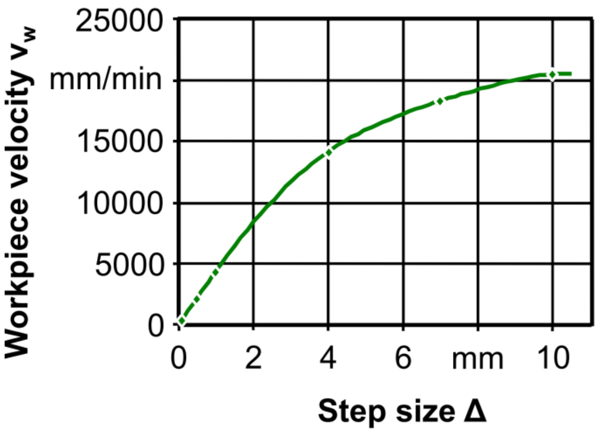


**Fig. 1.8** Dependency of the workpiece velocity on the selected step size [8]

### *1.2.4 Thermal Machine Tool Behavior*

Heat affects the static and dynamic properties of machine tools. The heat-related deformation on the machine components varies according to the material properties, the machine´s geometry and the conditions of the heat transfer. Consequently, the stiffness of the machine components is affected by the temperature. This has an impact on the production process and leads to dimensional deviations of the workpiece. The heat sources can be classified into internal and external sources according to where the heat is generated.

The internal heat sources include thermal dissipation losses, which have their origin in the limited electrical and mechanical efficiency of the machine components. The external heat sources result from heat transfer mechanisms such as conduction, convection or radiation caused by ambient heat flow. In addition, the process-induced energy losses due to the friction between the tool and the workpiece as well as the process heat have an impact on the temperature field of the machine [9]. Temperature measurements on machine tools and machining centers can be carried out according to the standards ISO 230-3 and ISO 10791-10 [10, 11]. The temperature distribution of the machine can be measured either at a finite number of individual points using thermocouples (contact measurement) or extensively via optical measurement systems (non-contact measurement via thermography camera / pyrometer) [12].

Especially the infrared thermography is applicable for this kind of measurement, for instance at press frames, because its surface has a homogenous radiance constant. Therefore, the emission factor of the radiating object, which can be determined by means of a reference measurement with an additional measuring system, has to be known. For the measurements of a finite number at individual points thermocouples or resistance thermometers can be used. These two types of temperature sensors differ in their measurement accuracy, cost, size, capability of measuring the surface temperature and vibration resistance (Tab. 1.1).

**Table 1.1** Comparison of contact and non-contact measurement of temperature [12]

| **Contact measurement** | **Non-contact measurement** |
|---|---|
| lower costs | no influence on measuring subject |
| more precise | local and extensive temperature measurement possible |
| easy to handle | |

Thermocouples are available for different applications and then classified into different types. For example, thermocouples of the type T have an accuracy of ± 0.5 °C for a measurement range between approx. - 200 °C and 300 °C. Furthermore, this type is capable of measuring temperatures in fluids such as in the lubricating oil system [13]. In Figure 1.9, some types of temperature sensors are shown.

For measuring the temperature of the main eccentric shaft of a press electrically insulated thermocouples with screw threads are often applied as close as possible to the shaft. This can be done by fixing the sensor directly to the bearing of the eccentric shaft within the press frame or the connecting rod. For measurements which do not allow a screwing fixation of the thermocouples the sensors can be fixed with a thermal conductance paste and adhesive tape [9]. The signals of the thermocouples can be recorded with a PC including a measuring board. The measuring board should be equipped with an internal cold-junction compensation, which is required for thermocouples. Within this compensation the reference temperature is simulated by means of an integrated transistor. The difference in temperature between the junction and the measurement point induces an electrical voltage. For the measurement of the oil temperature in larger containers electrically-shielded resistance thermometers can be applied [13].

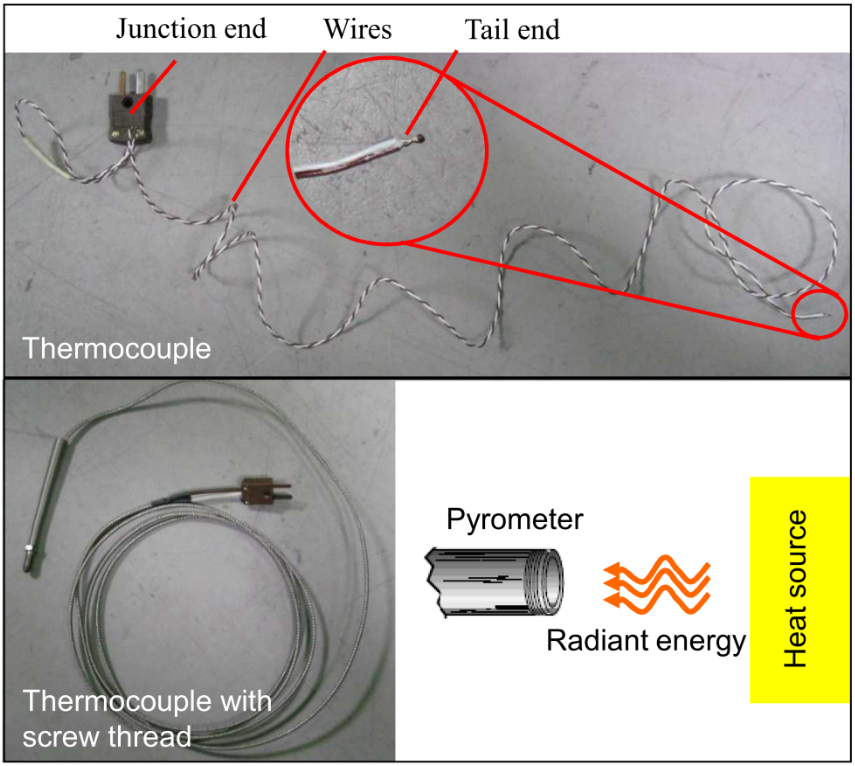


**Fig. 1.9** Different types of temperature sensors for measuring the temperature of machine tool components

To consider thermal convection effects the temperature of the environment is defined as the reference. The characteristic temperature profile of a machine converges exponentially with time. The temperature at the components of the machine rises with high gradients during the starting phase of the machine in usage and converges gradually with further operating time towards a certain value. The temperature gradients and the end temperature are much higher for machine tools used for machining than for those used in metal forming. For the determination of a steady thermal condition of the machine the temperature increase of all relevant machine components has to be taken into account. Once a steady thermal condition is reached the production process of the workpiece is no longer influenced significantly by temperature effects. Figure 1.10 shows the different thermal conditions of a high speed stamping machine [9].

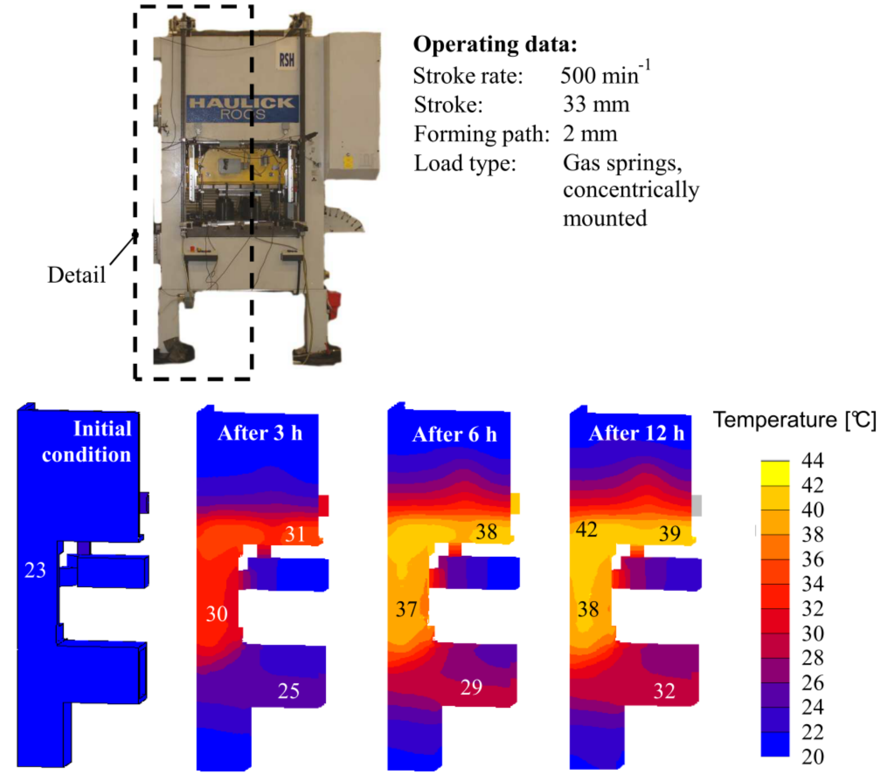


**Fig. 1.10** Temperature profile of a high speed stamping machine [9]

## 1.3 Process Analysis

As depicted in section 1.2., precise knowledge about the machine tool structure is essential in order to achieve the best productivity and accuracy. Since the machine tool behavior interacts with the machining process, characteristics such as thermal, statical or dynamical loads have to be taken into consideration. Therefore, an experimental determination of process factors has to be carried out. The measured data such as process forces, temperatures, sound and vibration can be used for parameter identification and the evaluation of process models. In conjunction with the identified parameters of the machine tool behavior the boundary conditions for comprehensive process machine interaction (PMI) models can be defined.

In the following section, different measurement methods for the analysis of process forces (see Sect. 1.3.1) are described. Measurement methods and applications of acoustic emission (see Sect. 1.3.2) and temperatures (see Sect. 1.3.3) are given consecutively.

## *1.3.1 Process Force Measurements*

Process forces are commonly used values for the characterization of manufacturing processes. Since there is a large variety of manufacturing processes where force measurements are of interest, the boundary conditions also differ. According to the different processes appropriate measuring devices have to be deployed considering the force magnitude and the process dynamics. For this purpose, the measurement procedure as well as the post-processing of the measured data may vary.

In this section, two commonly used measurement methods are described, which can be applied to cutting and forming processes. Subsequently, examples of force measurements covering a force bandwidth from a few tenths of newtons to several kilonewtons are given.

### 1.3.1.1 Force Transducer based on Strain Gauges

This kind of load cell consists of a steel body – the sensing device – which acts as a spring. On this body, strain gauges are applied as measuring devices. Thus, the forces are converted into elastic deformation. A calibration permits the correlation between the elastic strains and the applied force [14].

The basic effect of a strain gauge is the change of resistance in an electrical conductor due to the effect of mechanical stress, discovered by Wheatstone and Thomson [15]. This change of resistance in a single wire is very small. For that purpose, metal strain gauges with "wound wires", which form a kind of grid, have been developed. For an efficient production the grids are manufactured by etched foil technology nowadays. Apart from metal strain gauges there are other types of electrical resistive strain gauges, e. g. semi-conductor and vapor-deposited strain gauges [16].

Strain gauge-based force transducers can be used for static and dynamic measurements and are available in a variety of scales with nominal forces from about 10 N up to 5 MN. This range can be necessary, for example, for the measurement of forming forces in cold forging. However, with larger nominal loads the height of the transducers increases noticeably up to about 180 mm at 5 MN. Via a measuring amplifier and an analog digital converter the output signal can be recorded and processed electronically.

### 1.3.1.2 Force Measurement Based on Piezoelectric Elements

The piezoelectric effect is based on an interaction between electrical field strength, electrical displacement and the mechanical factors displacement and stress. If the piezoelectric element, e.g. quartz, is deformed mechanically, atoms in the crystal lattice are displaced. This leads to an outward charge displacement. Piezoelectric force transducers usually use the longitudinal effect in one direction. Long lasting quasi-static measurements require special attention to avoid drift of the output signal. A detailed description of piezoelectricity and measuring with piezoelectric sensors is given in [17].

Piezoelectric measurement devices, e.g. load washers and dynamometers, do not need a sensing device showing a considerable elastic deflection, which the measuring devices are applied on. In this case, the piezoelectric element itself is exposed to the force and also emits the electric output signal. Piezoelectric measuring devices possess a high stiffness and can be manufactured in a very compact design. Since they cover a large range of force magnitudes, which can be measured at high sampling rates they are predestinated for the use in processes with interrupted cutting conditions. The high resolution is also advantageous for measuring very small cutting forces as they occur, e.g. in ultra precision cutting. Compared to force transducers based on strain gauges, quartz load elements at a comparable measuring range for forming processes have a more compact design and a higher stiffness. However, piezoelectric force transducers are more expensive.

#### 1.3.1.3 Force Measurement in Ultra-Precision Machining

In ultra-precision machining, all process parameters are - compared to conventional machining - reduced or scaled down to some extent, e.g. cutting depth and feed rate range within a few microns only. Thus, the process forces $F_i$ are very small as well ($F_i \leq 1.5$ N). For this reason, dynamometers with the capability of detecting very small forces in the specified range are required, e.g. the triaxial dynamometer described in Chapter 15 (piezoelectric, Kistler Type 9256A1, which has a threshold of less than 0.002 N).

For most of the ultra-precision machining applications low rotational speeds (150 rpm (≈ 2.5 Hz) $< n <$ 5000 rpm (≈ 83.33 Hz)) are used. Therefore, process-induced dynamic excitation with frequencies $\nu > 100$ Hz can be neglected for ultra-precision turning, given a continuous cut. Due to unbalances the machine tool is excited by the rotation of the workpiece. For processes with discontinuous cut (e. g. eccentric turning, circumferential milling (fly cutting)) an impact excitation affects the tool and the machine tool whenever the tool engages the workpiece.

One major issue in measuring the forces for ultra-precision machining is the post-processing (Fig. 1.11) of the data obtained. As the forces are very small, external sources (e. g. current flow of the cross table) can add noise to the measurement data. To remove this noise low pass filters are used with cut-off frequencies of the filters depending on whether the dynamic influences of the unbalances are of interest or not.

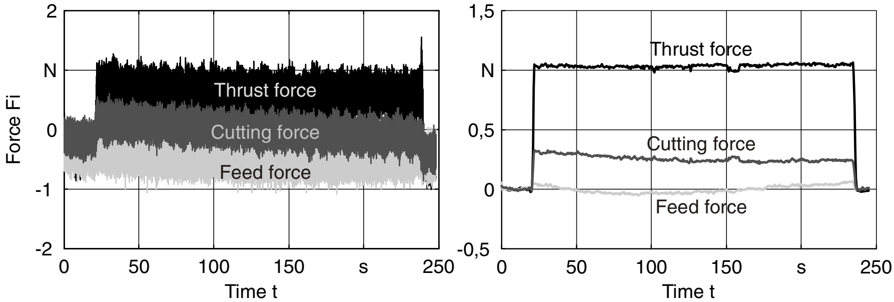


**Fig. 1.11** Measured forces before (left) and after post-processing (offset and drift removed, low-pass filter applied)

#### 1.3.1.4 Force Measurement in Micro and High Speed Cutting (HSC) Milling

For the force measurement of processes with interrupted cutting conditions at high spindle speeds some particularities have to be taken into consideration. Due to the periodical tooth engagement the machine tool structure is excited by high dynamical loads. Depending on spindle speed and number of cutting teeth the tooth passing frequency may achieve values of up to several kHz. Since the cutting force does not match an ideal sine wave the force signal also contains the harmonics of the tooth passing frequency. Thus, if the actual cutting force has to be measured, a very high sample frequency must be chosen. Another problem occurs when the tooth passing frequency exceeds the measurement device's eigenfrequency. Therefore, it is also very challenging to obtain time signals of the actual process forces acting on the cutter (e. g. to compare them with simulated force signals). However, in a lot of cases it is much easier and less error-prone to evaluate low-pass filtered or averaged signals (e. g. to identify cutting force coefficients).

Dynamometers based on piezoelectric elements are the most suitable solution in terms of the highest possible eigenfrequencies and of achievable measuring resolution. The measuring device is usually located between the machine table and the workpiece. Solutions for force sensors integrated into the tool holder are also available.

#### 1.3.1.5 Force Measurement in Cold Extrusion

Measuring the forces in cold extrusion processes requires the consideration of the following specific process characteristics: The high flow stress in cold forging due to forming at room temperature leads to high forces even if the die dimensions are small. In the full forward extrusion process investigated in the project "Optimization of Tool and Process Design for the Cold Forging of Net-Shape Parts by Simulation" (chapter 19), forces of about 200 kN occur with a die diameter of only 12 mm above and 6 mm below the die shoulder. Thus, force transducers with a high load capacity are necessary. Because of the high forces the presses and tooling systems in use have to be stiff and compact. As a consequence, only limited space is available for the force measurement. In contrast, the quasi-static characteristic of extrusion processes with a smooth force increase does not imply high demands on the dynamic behavior of the load cells.

Figure 1.12 shows the measurement setup in a tooling system for lateral cold extrusion. The use of quartz load washers is required due to the limited height in the press. The closed-die tooling system will be used on a single-acting stroke-controlled press. The press has to apply the closing force, via disc springs, and the forming force at the same time. To be able to measure both forces two quartz load washers 9091A from Kistler Instrumente GmbH (nominal force 1200 kN) with a height of only 28 mm are used. The washer (1) on the top is for measuring the entire press force, the one (2) between the top tool plate and the disc springs for the closing force. Subtracting these forces from each other leads to the punch force. With the presented tooling system interactions between process, tool and machine in closed-die forging will be investigated in the above-mentioned project (see chapter 19).

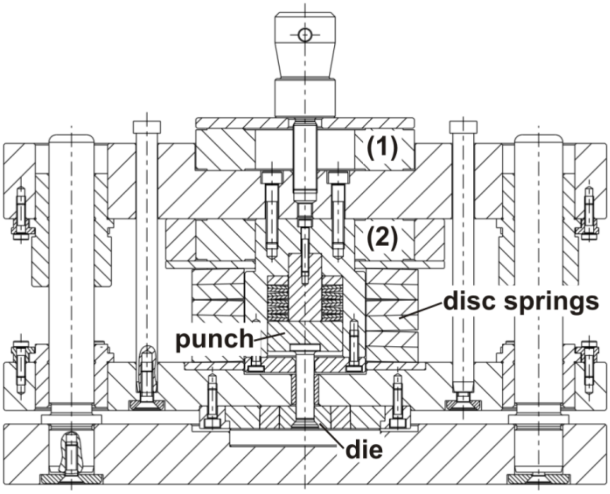


**Fig. 1.12** Tooling system for closed-die lateral cold extrusion with two quartz load washers Kistler 9091A (1 and 2) for measuring press force and closing force

### *1.3.2 Acoustic Emission (AE) Measurements*

Sensors for acoustic emissions to monitor process noise emitted during machining and forming processes are vibratory systems. Their resonance points are determined by their construction. As a result, these sensors, which work proportionally to acceleration, represent filter systems that have a dampening or amplifying effect according to the frequency range. The AE sensor thus determines the evaluable frequency spectrum by its frequency behavior to a great extent [18].

Acoustic emission Sensors are used in machining for different operations:

- first contact control,
- collision monitoring,
- balancing of grinding wheels,
- dressing monitoring in grinding,
- chatter detection,
- monitoring of grinding wheel wear and
- process monitoring of forming processes.

In the project "Process Machine Interaction in Speed-Stroke Grinding" the AE-signal was used as a trigger signal (see Sect. 5.2). As the contact times between the grinding wheel and the workpiece are in the range of milliseconds, the run-in and run-out phase can take less than 2 ms. Hence, the sensitive AE-signal was used to identify the exact moment of the first contact, which alleviates the analysis of the force measurement.

## *1.3.3 Process Temperature Measurements*

Various methods and techniques are used to conduct temperature measurements. One possible method is the use of thermo-chromic colors with special coating materials, which indicate changes in temperature by changing the color or tone [19]. Frequently used current methods are thermo-electric and radiation measurement methods [20]. The so-called tool-workpiece-thermal elements and thermocouples are used in thermo-electric measurements [21]. Pyrometry involves a non-contact measurement of the absolute temperature; i. e. the self-radiation of the body is measured without contacting the object itself [22]. In contrast, thermography involves a measurement of the temperature distribution, i. e. relative differences in temperature are measured but not, as in pyrometry, the absolute values. The radiation measurement methods in general have a significantly higher time resolution in comparison to thermo-electric methods. However, pyrometry is faster than thermography due to its simple setup. Moreover, these are non-contact measurement methods, which guarantee a considerably higher flexibility of the measurements. Non-contact measurement methods exhibit a specific measuring error due to a surface layer that forms in free air on the surfaces to be measured. In recent years, the measurement of cutting temperatures by means of pyrometry and thermography has gained considerable importance. A short overview of the used methods of temperature measurement for cutting and grinding is given.

### 1.3.3.1 Investigation of the Temperatures in Cutting

Thermocouples have a relatively low time resolution and it is difficult to place them directly in the cutting zone. Single-wire thermal elements represent an exception since they can easily be placed in the secondary cutting zone [23]. The main problem for both of these methods as well as for the tool-workpiece-thermal element measurement method is the calibration of the measuring chain. Hence, these measurement methods are not commonly used. Only an average cutting temperature is measured in the contact zone when the tool-workpiece-thermal element method is used [21].

### 1.3.3.2 Investigation of the Temperatures in Grinding

In grinding, the major part of energy input is dissipated as heat. The heat flows into the chips, the coolant, the environment, the workpiece and the grinding wheel. The degree of thermal damage of the workpiece surface depends on the machining parameters. Diffusion, chemical reaction and soft annealing appear in the contact area as a result of thermal stresses. These effects depend exponentially on the heat development [24]. The productivity is limited by the heat development at increasing process parameters [25]. The quantification of these thermal effects in grinding can be applied to specify the workpiece properties which are subsequently required in the application [26]. Based on this knowledge, simulations can be implemented to determine adequate parameters for the NC-machine in advance. One method for determining the transformation of the microstructure by heat input is to examine micro-sections [27].

An overview of different methods for temperature measurements is presented in [28]. Temperature measurements in grinding are primarily performed using thermocouples and thermographic cameras. The disadvantage of these temperature measurement methods is that the temperature can only be determined at the workpiece. The best results using thermocouples are achieved using epoxy resin for fixation [29]. Temperature measurements on the workpiece surface using a thermographic camera are influenced by the coolant supply, which affects the workpiece surface. Therefore, the workpiece has to be isolated from the coolant supply [30, 31]. An option is to transport the infrared radiation from the contact area by means of a glass fiber [32]. A further development is to measure directly inside the grinding wheel using micro sensors. Here, the temperatures are measured in-situ in the contact area between the grinding wheel and the workpiece. The measurement signal is transferred by complex equipment in the grinding wheel; therefore the temperature measurement is very complex [33]

#### 1.3.3.3 Experimental Investigation of the Temperature in the Cutting Zones

To determine the temperature in the cutting zone, experimental investigations are conducted by means of semi-artificial thermocouples [34-36]. This method can be used to investigate the temperature distribution in the workpiece and in the chip. One leg of the thermocouple is made of constantan wire, the other from the material to be machined. The basic scheme of this measurement method is shown in Figure 1.13 a. According to the scheme the wires are welded to the workpiece with a condenser welding machine. Each constantan leg is placed on a preset height $h_i$ and length relative to the border of the workpiece. If the exact start of the measurement, which is determined by a trigger signal, and the cutting speed are known, the distances $l_i$ can be calculated. Thus, the exact position of the individual constantan legs relative to the point of the wedge can be calculated and the exact position of the point is to be measured accordingly. A specimen with the welded constantan wires is shown in Figure 1.13 b.

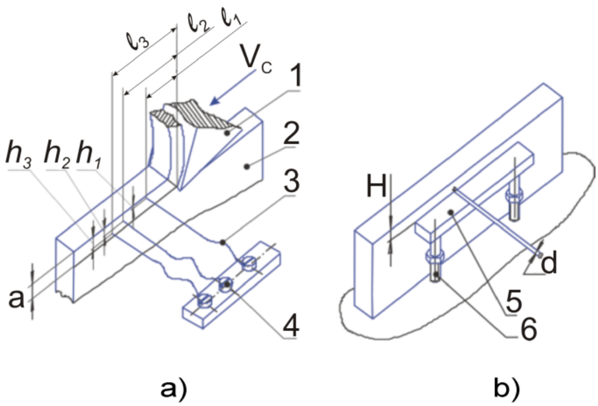


**Fig. 1.13** a) Scheme of the setup for temperature measurement and b) workpiece with welded thermocouples

In this example, C45 was used as test material and the standard carbide plates P20 of the company Walter AG were used as inserts. A value of 5° was selected for the rake angle and a value of 8° for the clearance angle. Characteristic temperatures in the primary cutting zone and in the chip are shown in Figure 1.14 [36]. Regarding the starting point of the cutting process, the temperature signal for the sensor position can be identified. Thus, the temperature in the cutting zones and in the basic material can be determined. The signal shape and the amplitude during cutting correspond to the position of the temperature sensor or the constantan leg respectively in the different layers of the material.

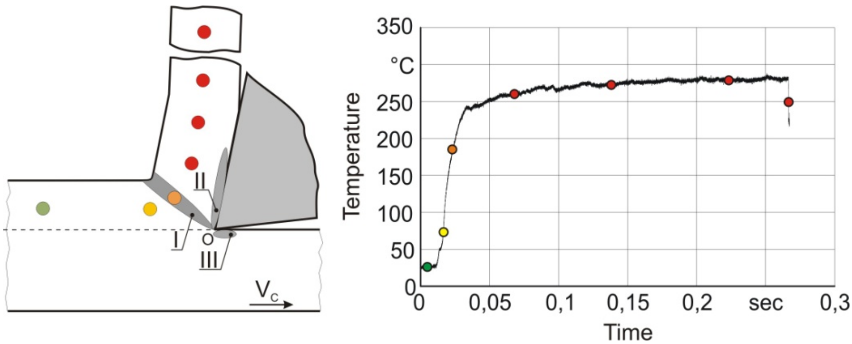


**Fig. 1.14** Characteristic signal profile in the primary cutting zone and in the chip

In practice, this method can only be applied for comparably large cutting depths to achieve reasonable results and so as to be able to determine the position of the constantan leg precisely. This method was used in [37] for the experimental investigation of the temperatures in the primary and tertiary cutting zone and in the base material.

## 1.4 Workpiece Analysis

Parts or their surfaces are machined to enable specific functions or tasks. Depending on these functions the geometry and/or the surface properties are specified. To validate whether the machined parts meet these specifications their properties have to be determined after machining. Below, examples are given, which describe the assessment of surface topography and part geometry. Additionally, some post-processing procedures are presented.

### *1.4.1 Surface Assessment*

The roughness of technical surfaces is commonly detected via tactile measurements. Therefore, the probe tip, usually a pyramid-shaped diamond, is moved over the surface of the workpiece at a constant feed rate. The topographical data is described by the vertical position shift of the probe tip with reference to the measuring position in the so-called primary profile. To gain the waviness and the roughness profile the measured data is processed with filters which are standardized within the ISO Standard 11562 [38]. The waviness profile is smoothed and yields long-wave information without roughness data. On the other hand, the roughness profile consists only of short-wave information without waviness data. The commonly used characteristic values of the surface roughness are derived from the roughness profile. These are the arithmetic mean surface roughness *Ra*, the ten-point height *Rz* and the maximum roughness *Rmax*. Of course, there are more roughness values available for various tasks having different specifications, which will not be mentioned and explained here.

The arithmetic mean surface roughness *Ra* is an integral value over the whole measuring length, which is also used in industrial application and in research. When calculating *Ra*, peak values, which can be disadvantageous for some applications, are averaged. In these cases, the ten-point height *Rz* is more suitable. To determine this value the whole measuring length is divided into five sections. In each section, the maximum roughness, i. e. the difference of the maximum and minimum height of the profile, is determined. The average value of these five values is called *Rz*. The maximum roughness *Rmax* is the difference of the maximum and minimum height of the profile over the entire measuring length. It is a very important value for technical applications such as sealing surfaces where peak values as well as outliers can lead to difficulties.

Further methods for surface assessment are optical measurement techniques like interferometry or white light interferometry. For the measurement a beam of light is divided via a beamsplitter to illuminate two surfaces - workpiece and planar reference. The reflected beams from workpiece and reference are recombined and directed to interfere at a detector. Depending on the phase shift of the measuring and reference beam typical fringe patterns can be observed, e. g. parallel fringes for tilted planar surfaces.

For white light interferometry (Fig. 1.15) the workpiece is scanned in vertical direction so that the light reflected from the surface points interfering with the reference beam at certain heights will be recorded as surface data. The interferometric measurement principle is only applicable for optical surfaces; it provides the same roughness values as mentioned above but considers an area instead of a line profile.

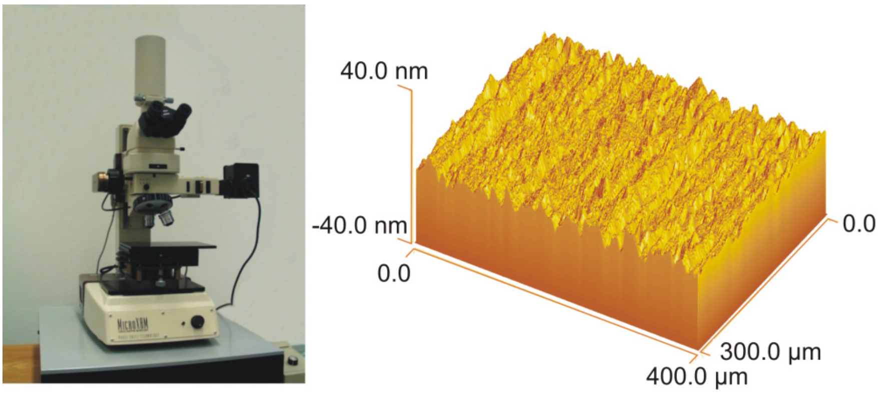


**Fig. 1.15** White Light Interferometer (left) and measured surface topography of a diamond turned sample (right)

The main advantages of optical measurements are the short measuring time (only a few seconds) and, most importantly for optical surfaces, the absence of any mechanical contact during the measurement. Therefore, the surface cannot be damaged. Another advantage is the possibility of obtaining spatial structure information for the surface topography instead of only 2-dimensional information (profilometry). One disadvantage is the low capability of measuring surfaces with high slopes which can occur e.g. for spherical, aspherical, structured and free-formed surfaces. If the slopes exceed a certain angle (typically > 15° to 25°) depending on the numerical aperture of the applied objective, the reflected light will not enter the microscope objective. For these areas, no measurement data is recorded.

### *1.4.2 Geometry Assessment*

Similar to the described surface assessment geometric measurements can be carried out either by using mechanical (tactile) techniques or optical techniques. Therefore, the same advantages and disadvantages apply. Additionally, a fast evaluation of complex workpieces with a high decomposition can be realized for optical geometry measurements.

White light fringe projection belongs to the 3-D imaging techniques, which can create a spatial exposure without the operation of additional axes. The application range of white light fringe projection lasts from quality conformance tests, reverse engineering and medical applications to archaeology.

A scanner reaching with white light fringe projection consists of a CCD camera and a projector. For the registration of a surface the projector generates a periodical equidistant interference fringe pattern. This projection is distorted by the object´s geometry. During the projection, the generated striped pattern is captured by the CCD-camera. The result of the distortion is a level difference in the structured image, which is a rate for the altitude $h$. The dimension $h$ can be calculated by the scanner software using the principle of triangulation. The distance between projector and camera is the length $L$ (see Fig. 1.16), and the operating distance $A$ can be found between the sensor and the surface area. The width of the measuring field is designated by $M$, while the angle $\theta$ is related to the position of the camera and the projector. The angle of projection α is between the projector and the surface area. The observation angle of the camera to the current measuring point is designated with $\beta$. The formula for the calculation of $h$ is given by [39]:

$$h = \frac{L \cdot \sin\alpha \cdot \sin\beta}{\sin(\alpha + \beta)}$$

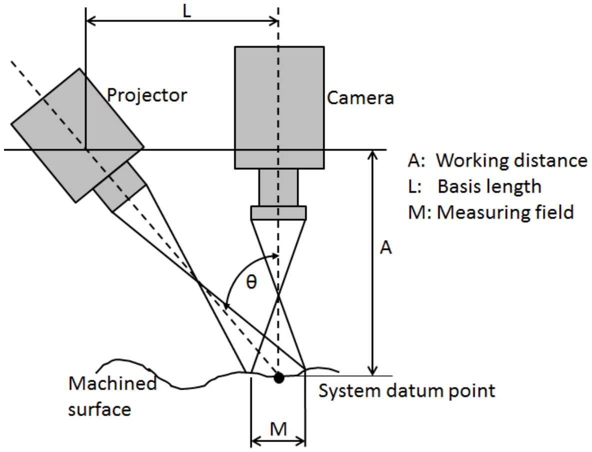


**Fig. 1.16** Measuring configuration of a white light fringe projection [38]

The workpiece is scanned from several different positions during the exposures. After the scanning process is finished the individual exposures are coarsely-merged to a 3-dimensional general view. This happens by means of characteristic features on the surface. Afterwards, a precision alignment algorithm is used. The calculated 3-D model can be exported. The scanner as well as the scanned part can be seen in Figure 1.17.


**Fig. 1.17** Scanner system (a) and a scanned workpiece (b)

The determination of the resulting deviation is evaluated by comparing the milled part with the reference model. For this purpose, the deviations of all dot pitches of the actual to the reference model are calculated and plotted in a false color image [36].

## 1.5 Conclusion

This chapter presents a general overview of the state of the art for different measurements and test techniques, which are used for the analysis of the interaction between process and machine tool structure. It has been shown that, depending upon a special process and machine tool, different measurement and test techniques can be used, depending on the special parameters to be determined. Additionally, this chapter provides information as to which measuring and testing procedures are used for the investigation of the process machine interactions.

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