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4.3
Cutting Processes

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4.3.1
Introduction

The mechanical removal of chips from the workpiece is called material removal. If the number of cutting edges and their macro-geometry and orientation are known, the operation is called a cutting process. These cutting processes play a major role in manufacturing because of their wide field of applications. Many different materials with a wide variety of shapes can be machined by cutting. Both roughing for high productivity and finishing to meet high precision demands can be achieved by cutting. A further distinction is made according to the number of cutting edges. Single-point cutting processes are turning as the most important method, planing and shaping. If more than one cutting edge integrated in a tool is contributing to the material removal, the process is called multi-point cutting. Milling, drilling, and broaching are the most important operations in this field. Any cutting process is possible only by applying forces to remove the chips from the workpiece. These forces may also cause deformations of the tool, the machine tool, or the workpiece, thus leading to dimensional errors on the part. The cutting energy, as a result of force application under specific speeds, is to a large extent converted to heat, which may cause thermal problems for the participating components. Mechanical and thermal loads are also responsible for a temporal change of the tool condition, leading to a change in the process output. Hence sensors are needed to monitor all the mentioned undesirable but inevitable changes of the process state to avoid any damage of equipment or machined parts.

4.3.2
Problems in Cutting and Needs for Monitoring

Major tasks, which should be attained with a monitoring system, are the detection of problems in the cutting processes and to gain information from the process condition for optimization. All cutting processes are subject to malfunctions, which lead to the production of sub-standard parts or even make it difficult to continue the process. Major problems can be related to the condition of the tool. Most critical conditions are tool breakage and the chipping of cutting edges. When these problems occur, the process should be immediately interrupted to change the tool. Therefore, the breakage and chipping of the cutting tool should be monitored and detected with high reliability. However, these failures of cutting tools made of mostly hard and brittle materials are stochastic processes, and therefore difficult to predict. Therefore, monitoring in this field is of great industrial interest [1]. The next important task is to detect the wear behavior of the tool. It deteriorates the surface quality of the machined parts and increases the cutting forces and heat generation during the process, resulting in an increase in machining errors. The tool wear is again a random process and hence the tool life is significantly scattered. Therefore, in industrial practice cutting tools are changed after a predetermined cutting time or number of machined parts, thus often wasting cutting capacity.

Formation of a built-up edge on the tool rake face, which is considered as adhesion of the workpiece material, is another serious problem in cutting processes because it also deteriorates the surface quality of the machined parts. The occurrence of this phenomenon depends on the combination of tool and workpiece materials and cutting conditions. In addition, it is affected by the supply of cutting fluids and the tool wear state. These overall tool-related problems are driving forces to develop suitable sensor systems to monitor cutting processes.

Furthermore, chatter vibrations might also occur, which can be distinguished as two types, forced vibration and self-excited vibration. Both of them will generate undesirable chatter marks on the machined surface and may even cause tool breakage. The prediction of these effects based on theoretical analysis is still difficult and thus a technique to detect any kind of chatter vibration is desirable. Other problems to mention are chip tangling and collisions due to NC errors or operator failure. Together with the ongoing trend to automate cutting processes as much as possible, all the above problems are major reasons to develop sensor systems for cutting process monitoring.

4.3.3
Sensors for Process Quantities

In any cutting operation, the removal of material is initiated by the interaction of the tool with the workpiece. Only during this contact can the resulting process quantities be measured. Their temporal and local course is determined by the effective quantities in the zone of contact, which may differ from the nominal setting quantities owing to internal or external disturbances.

The most important process quantities to be detected are forces, power consumption, and acoustic emission [1]. However, vibrations and temperatures resulting from material removal are also of interest. In the following, sensors developed to measure these different process quantities will be introduced. Figure 4.3-1 shows an overview of possible positions for sensors to determine these quantities. In a schematic set-up a portal milling machine and a lathe are equipped with different sensors for force, acoustic emission, torque, power, and vibration measurement.

4.3.3.1 Force Sensors

During material removal, the cutting edge penetrates the surface of the part to be machined owing to the relative movement between tool and workpiece. The tool applies forces to the material, which result in elastic and plastic deformations in the shear zone and which lead to shearing and cutting of material. The process

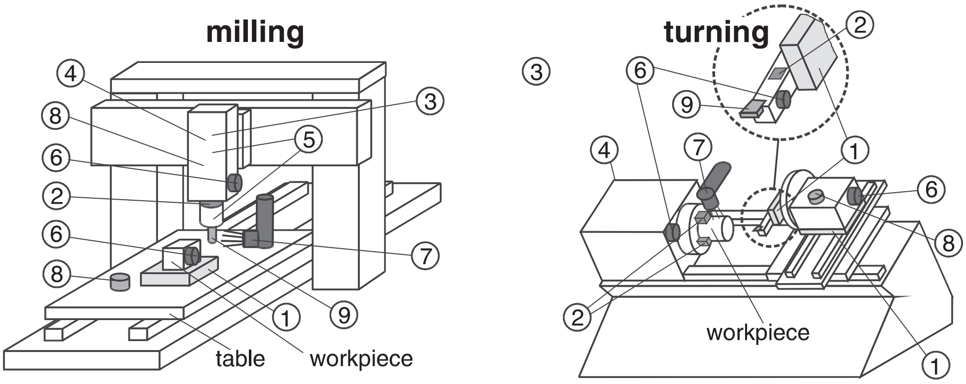

Fig. 4.3-1 Possible sensor positions to measure process quantities during cutting
① piezo-electric dynamometer platform type; ② strain gauge-based force measurement; ③ force measuring bearing; ④ power sensor; ⑤ torque sensor; ⑥ AE-sensor, surface mounted; ⑦ AE-sensor, fluid coupled; ⑧ acceleration sensor; ⑨ tool inbuilt sensor

behavior is reflected by the change in the cutting forces, hence monitoring of this quantity is highly desirable. Cutting forces have to be measured continuously. The signal evaluation can be done in different ways. Static force analysis is necessary, eg, to describe the influence of the workpiece material. Knowing the static force components, it is possible to determine the specific cutting force k_c for different materials under defined cutting edge geometry and cutting conditions [2]. They are also essential to describe the influence of different cutting parameters such as cutting speed, feed or depth of cut, and also the influence of different cutting tool materials and geometries. A more complex evaluation of the dynamic force components is applied to gain more knowledge about the current cutting tool condition. It is the purpose to detect tool chipping or breakage, the occurrence of chatter vibrations, or changes of chip breaking as fast as possible during operation to avoid any damage to the workpiece or other involved components. Different methods have been applied for further force signal processing such as frequency analysis and cepstrum analysis. Artificial intelligence techniques such as neural networks, fuzzy set theory, and combinations of the two methods have also been applied to the cutting force signals.

Whereas for the measurement of cutting forces during turning it is relatively easy to mount the tool shank on any kind of measuring system (Figure 4.3-1, right), a force measurement during milling is more complicated. Often the forces are measured with a sensor system mounted on the machine table in a stationary coordinate system (Figure 4.3-1, left). Owing to the rotation of the tool, a transformation of the force components according to the current cutting edge position is necessary. Another possibility is the simulation of a milling process by a turning operation with interrupted cut, where the milling cutting frequency is achieved by an adapted number of rotations of a workpiece with additional stripes to achieve a defined ratio of material and gaps at the circumference [3]. For larger inserted tooth cutters there is a possibility of integrating a sensor system behind one individual cutting edge.

Most of the first approaches to measure forces were based on strain gage methods. The main disadvantage of this technique is that the best sensitivity can only be achieved by applying strain gages to elements under a direct force load with reduced stiffness to generate measurable strains. Most often strain rings were used, which led to a significant weakening of the total stiffness. Owing to improvements in the sensitivity and size of strain gages, this difficulty could be reduced. In the latest applications of this method for turning a wireless transmission of the signals from the strain gages in the tool shank is realized by infrared data transfer [4]. However, for this process a different approach is also possible. Strain gages have been applied to a three-jaw chuck on a lathe for wireless force measurement during rotation of the workpiece [5]. Furthermore, an integration of strain gages in tool holders for milling with wireless data transmission has already been introduced to the market [1]. In addition to axial and radial forces, the torque can also be measured. Each tool requires to be fitted with the sensor system, which limits this approach to laboratory use.

A very reliable and accurate method is the application of piezoelectric quartz force transducers. In a dynamometer of platform type, four transducers based on this piezoelectric effect, being able to measure in three perpendicular directions, are mounted on a base plate and covered with a top plate under significant preload. These platforms are available in different sizes and are extremely stiff. They can therefore be mounted in the direct flux of force without significantly weakening the structure. Even the problem of complete protection of these sensitive transducers against coolant flow of any kind has been solved in recent years. As already mentioned, during milling or drilling a dynamometer platform is most often placed on the machine table underneath the workpiece (eg, [6]) (Figure 4.3-1, left). In turning a small dynamometer is often applied between the shank and the turret (eg, (7]) (see Section 3.3.3.1). Exemplary results of a dynamometer-based force measurement in turning and milling are shown in Figure 4.3-2. The results of hard turning reveal a linear increase in the cutting force with increasing feed for two different depths of cut [7]. In milling of high-strength steel the superior behavior of PCBN cutting tools compared with tungsten carbides and cermet is demonstrated by evaluating the maximum cutting force [6].

An installation of a piezoelectric-based dynamometer between the cross slide and the tool turret has been reported. Lee et al. performed an FEM analysis to identify the best position of the piezoelectric sensor underneath the turret housing [8]. Ziehbeil chose a special application of piezoelectric quartz force transducers in the field of fundamental research [9]. His attempt was to separate thermal and mechanical influences on the tool rake and flank face by applying adapted sensors. For the stress distribution evaluation he used a split cutting tool (Figure 4.3-3, left). The necessary force distribution on the rake and flank face was determined by four independent piezoelectric elements. With this set-up it is not directly possible to measure the normal and tangential force component on each face, because both tool parts interact due to the contact in the parting line. However, by using an adapted calibration matrix and procedure and by limiting the tests to orthogonal cutting, it was possible to determine the normal and tangential

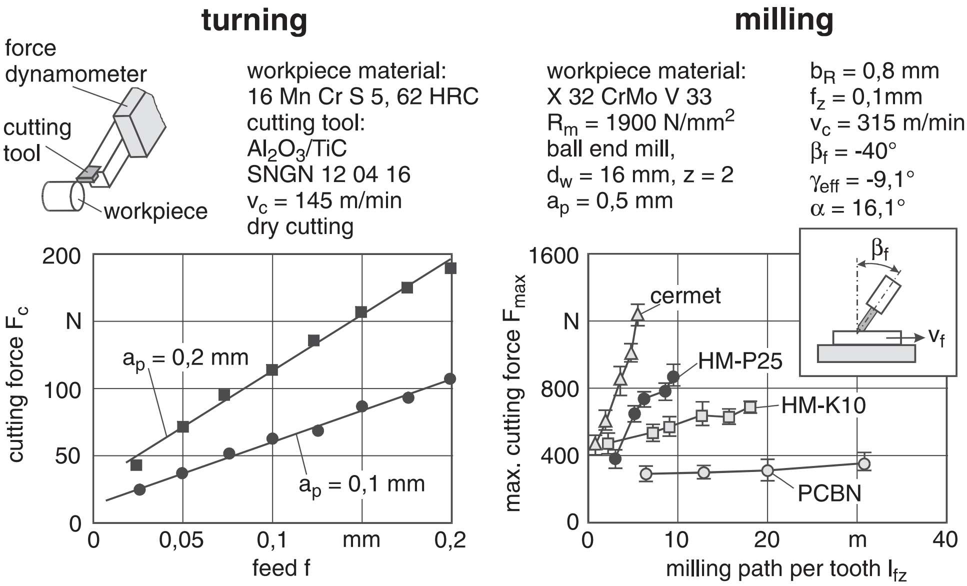

Fig. 4.3-2 Dynamometer-based force measurement in turning and milling. Source: Brandt [7], Hernández [6]

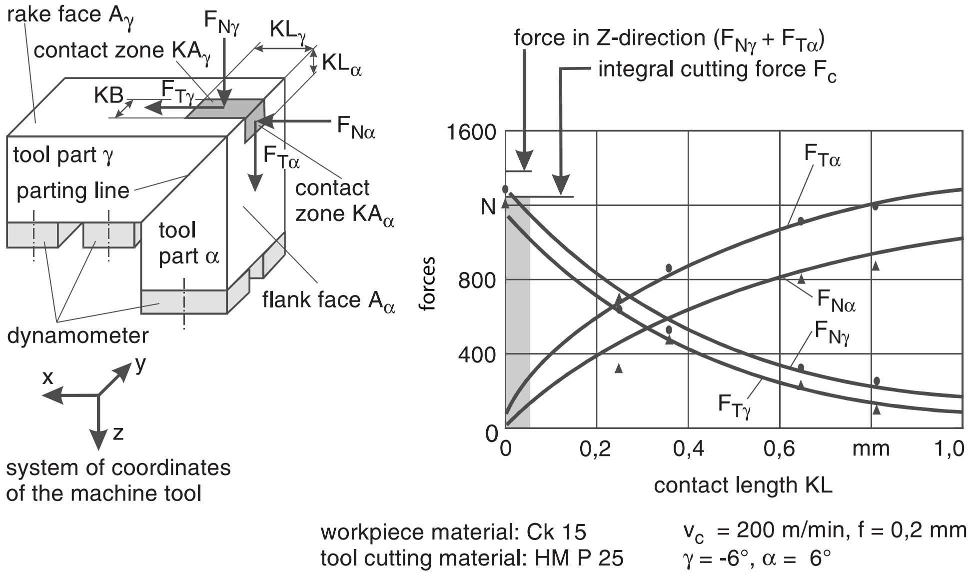

Fig. 4.3-3 Piezoelectric force measurement on a split tool. Source: Ziehbeil [9]

force components $F_{N\gamma}$ and $F_{T\gamma}$ on the rake face and $F_{N\alpha}$ and $F_{T\alpha}$ on the flank face. Figure 4.3-3 (right) shows the result of measurements with different parting line positions. For comparison, the integral cutting F_c is also shown; the results of the split tool are nearly identical. These forces together with the corresponding cutting lengths were used to calculate the stress distribution. The most complex dynamometer development so far is a rotating system for milling applications. It consists of four quartz components for the measurement of forces and torque.

Also, four miniature charge amplifiers are integrated in the rotating system and the transmission of data is realized via telemetry. This system is especially attractive for five-axis milling, where the force transformation from a stationary platform-type dynamometer is extremely complex.

Direct force measurement using stationary dynamometers can be regarded as state of the art. They are widely used in fundamental research, but their application in industrial production is very limited for basically two reasons. First, these systems are only available at very high cost, and second, no overload protection is available, leading to severe damage of the dynamometer in the case of any operator or machine error [1]. For this reason, platform- and ring-type sensors based on quartz transducers or strain gages have been implemented in shunt with the process forces [1, 10]. They are mounted either behind the spindle flange of milling machines or at the turret interface on lathes. These sensors are overload protected, because they are only subjected to a small part of the load. Although commercially available, these sensors still do not work reliably owing to their sensitivity to many disturbing factors such as coolant supply or thermal expansion of components.

Force measuring bearings have also been introduced, either with strain gages at circumferential grooves of the bearing ring or in an additional bushing [1]. Owing to the necessary filtering of the obtained signal to eliminate the ball contact frequency, they are not able to measure high-frequency signals. Furthermore, the rigidity of the spindle is reduced, which limits this method to a very few cases.

Another method for force monitoring became possible with the introduction of spindles with active magnetic bearings. By evaluating the power demand of the stationary magnets at the circumference of the rotor to keep it in a desired position with constant gaps from the different magnets, the cutting forces can be determined without further equipment [11]. These spindles are very attractive, especially for high-speed cutting, because they allow rotational speeds of more than $100\,000\ \text{min}^{-1}$. However, the high cost of this spindle type limits their application to a very few cases at present.

Force dowel pins or extension sensors detect the cutting force indirectly if they are correctly applied to force-carrying components. However, the effort to find the most suitable fitting position and the poor sensitivity limit the application of these sensors in many cases to tool breakage detection during roughing processes [1]. Husen [12] used dowel pins for strain measurement in the housing of a multi-spindle drilling head. It was possible to detect individual tool breakage on eight different spindles by applying only one sensor [12].

Summarizing the available sensor solutions for direct force measurement, it can be said that piezoelectric transducers can be regarded as the most suitable but most expensive solution. The application of strain gages is also very popular, and sufficient sensitivity can be achieved without severe weakening of the total stiffness. Solutions integrated in the tool or tool holder are complex and expensive, which limits their application to laboratory use.

4.3.3.2 **Torque Sensors**

The measurement of torque is most suitable for drilling and milling processes. Several different principles can be applied. One attempt was to integrate two preloaded piezoelectric quartz elements in the main machine spindle [13]. However, the high effort and the additional required space are limiting factors. A spindle-integrated system incorporating a torsional elastic coupling or two toothed discs or pulleys was also introduced, but the practical use is again limited for the abovementioned reasons [1].

A brief explanation of sensors integrated in the tool holder was given in the previous section. Either rotating systems with piezoelectric transducers or with strain gages are also able to measure torque. A complex sensor based on strain gages for torque and thrust also incorporating thermocouples for temperature measurements was introduced [14]. Furthermore, a special piezoelectric dynamometer for torque measurements is available, which operates stationary and has to be placed underneath the workpiece on the machine table. It is used in fundamental investigations for drilling processes. A different approach for torque measurement has been published [15]. The supervision of the main spindle rotational speed by using a pulse generator in the spindle motor was proposed. By investigating the fluctuation pattern of the signal during one revolution and applying a vector comparison algorithm, it was possible to determine tool breakage and chatter vibrations.

Two other techniques are based on magnetic effects and will be explained below.

The first sensor uses the magnetostrictive effect [12]. The permeability of ferromagnetic materials changes under mechanical load. Changes due to torque load on the shaft of a drill can be detected by applying an adapted system of coils. One excitation coil and four receiving coils are integrated in a miniature sensor system, which is able to measure on drills with a diameter of 2.0 mm or more. The measuring distance is 0.5 mm (Figure 4.3-4, left). Figure 4.3-4 (right) shows an exemplary result of one drilling operation. The results reveal that by analyzing the torque sensor signal in the time domain it is possible to detect process disturbances. Transient torque peaks in an earlier state (c) indicate the occurrence of continuous chatter in state (d) due to reduced cutting ability. These torque peaks are related to the drilling depth, tool type, and wear state regarding their form and distribution. Typical frequencies were found between 200 and 600 Hz. Monitoring of the lifetime of a drill is therefore possible. With the sensor indication the drill can be removed from the machine tool before tool breakage or workpiece damage occurs. Owing to the small size of the sensor with a diameter of 5 mm, integration in almost any machine tool environment is possible. Parallel monitoring of different drills in a multi-spindle head may also be considered, although Husen [12] has developed a special solution based on strain dowel pins for this application.

The second solution is based on magnetic films, which are deposited on the tool shank [16] (Figure 4.3-5). Torque of the shaft due to mechanical load will lead to a change in the permeability of the films. The films are magnetized with the

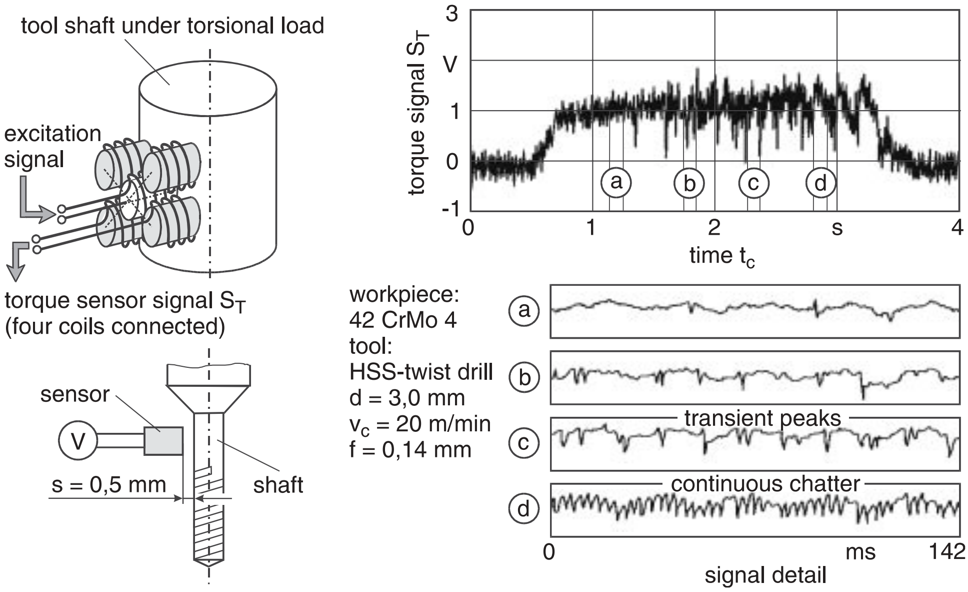

Fig. 4.3-4 Magnetostrictive torque measurement on small twisted drills. Source: Husen [12]

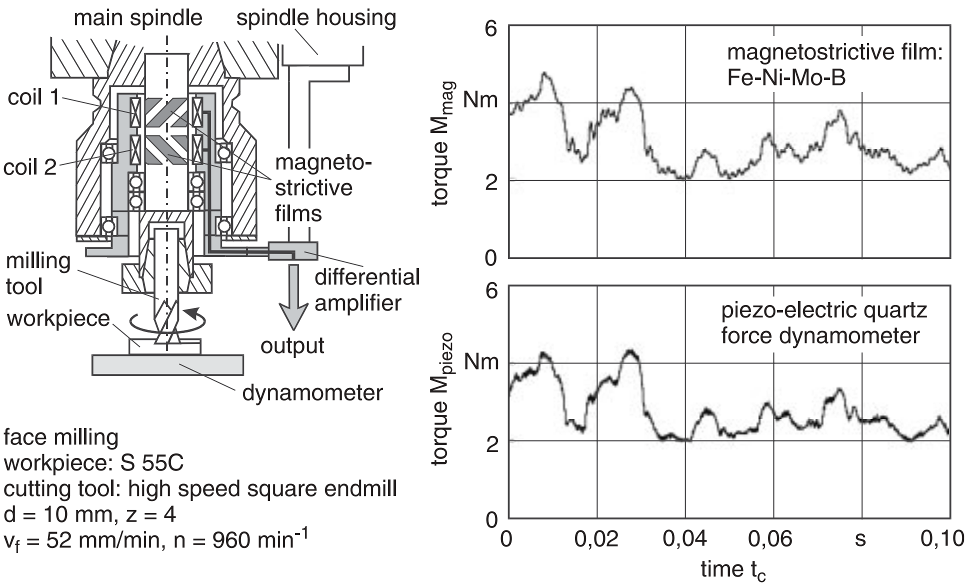

Fig. 4.3-5 Torque measurement based on a magnetostrictive film sensor. Source: Aoyama et al. [16]

surrounding circular coils. Owing to the different orientations of the upper and lower film, this sensor system is very sensitive to the torque load on the shaft by using an adapted bridge circuit. The material for the film Fe-Ni-Mo-B was chosen because of its high sensitivity and low hysteresis loss. Figure 4.3-5 (right) shows the results of a milling test. The signal of the magnetostrictive film sensor is compared with the measurement of a stationary piezoelectric dynamometer, placed underneath the workpiece. The face milling experiments demonstrate the sensitivity of the magnetostrictive sensor and the suitable dynamic characteristics. Even experiments with spindle revolutions of 3500 min^{-1} could be performed successfully [16]. The major disadvantage is the high effort to install the system with the need to modify the spindle end. Also, the necessity for additional bearings limits the possible maximum spindle rotation.

To summarize the available solutions for torque measurement, it can be said that expensive piezoelectric or strain gage-based systems are available which offer the necessary functionality. For laboratory use other complex systems have shown suitable performance. The most promising low-cost version for industrial use seems to be the non-contact magnetostrictive sensor with five coils, because this solution does not need any major changes to the machine set-up.

4.3.3.3 **Power Sensors**

The measurement of power consumption of a spindle drive can be regarded as technically simple. Depending on the type of system used, current, voltage, and/or phase shift can be detected. The sensors are not even located in the workspace of the machine tool and therefore have no negative impact on the process. Also, the amount of investment is very moderate, thus making this sensor type attractive for industrial application. It is even possible to gain information about the actual power demand from the drives from the machine tool control without additional sensors. However, the sensitivity of this measuring quantity is limited, because the power required for cutting is only a portion of the total consumption (see also Section 3.3.3.2). Most often power monitoring is used to prevent overload of the spindle and to detect collisions. Nevertheless, attempts have been made to use the motor current of the feed drive in milling to determine process conditions and tool breakage. Using permanent magnet synchronous AC servo motors for direct drive of the feed axis the dynamic changes of the current can be determined. By applying special algorithms, which include the average cutting force residuals and the force vibration of each cutter, a successful determination of tool breakage from the current measurement is possible. Further developments in the field of dynamic drive systems in combination with the latest machine tool controls will further increase the importance of this monitoring strategy, even without additional sensors.

4.3.3.4 **Temperature Sensors**

As already explained in Section 3.3, every cutting process generates a significant thermal impact on the workpiece material. The measurement of the temperature distribution in the cutting zone is therefore of great importance for the fundamental understanding of tool wear and workpiece surface integrity. A distinction in measuring systems based on heat conduction or heat radiation can be made [2]. The most popular systems are shown in Figure 4.3-6. The systems based on heat conduction use the thermoelectric effect. Direct methods are the single-tool and the twin-tool methods.

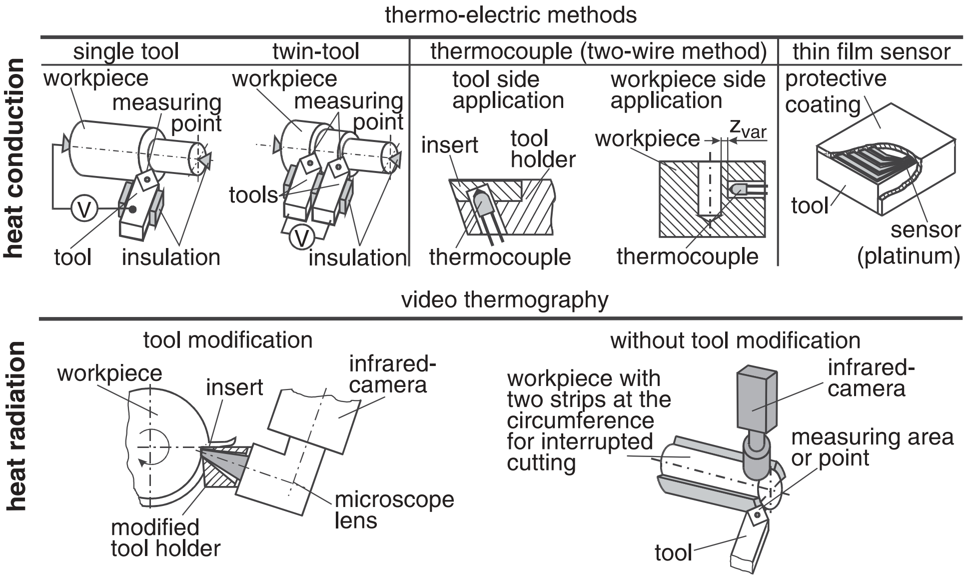

Fig. 4.3-6 Temperature-measuring systems in cutting

The effect is based on the fact that workpiece and tool material form a thermocouple in the heated contact zone. A second contact point has to remain at a defined temperature to determine the average temperature in the cutting zone by measurement of the thermal voltage after calibration. The major problem for the single-tool method is the insulation of the relevant components and the calibration. Any kind of temperature distribution is not detectable. The method is furthermore restricted to electrically conductive materials. Another method is to integrate a thermocouple in the tool or the workpiece. In case of a single-wire method the conductive tool material or the contacting chip will serve as the second element of the thermocouple. If several thermocouples or different measurement positions are applied, a temperature distribution can be determined. A method for the evaluation of the temperature distribution in the cutting zone is based on thin-film sensors [9]. The ohmic resistance of pure metals such as platinum changes with variation in temperature, while a pressure influence can be neglected. A layer of 12 platinum sensors with a thickness of 0.2 μm and a width of 25 μm at a distance of 0.1 mm to each other was evaporated on an Al_2O_3 cutting tool and protected by an additional 2 μm coating of Al_2O_3 on top (Figure 4.3-7, left). The results reveal that it is possible to determine the local temperatures at the rake face even at a cutting speed of 800 m/min (Figure 4.3-7, right). The measured temperatures are slightly higher than the melting point of the machined aluminium alloy at normal pressure, but melting of the chip bottom surface was not observed. The melting temperature of the material is shifted towards higher values because of the high mechanical load in the zone of contact. The pressure in the corresponding area has been determined to be in the region of 500 MPa [9]. This sensor development helped considerably in understanding the fundamentals of cutting and in calibrating simulation programs [17]. Unfortunately, it is not possible to machine harder materials than the chosen aluminium alloy, because

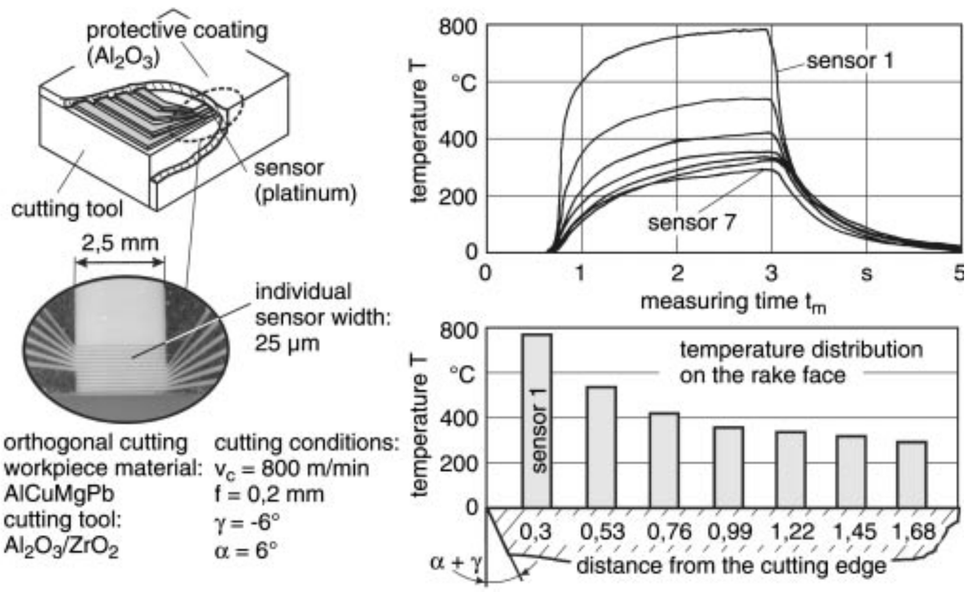

Fig. 4.3-7 Thin-film sensor for temperature measurement during orthogonal cutting. Source: Ziehbeil [9]

the protective layer is exposed to fast wear if steel materials are cut. The basic idea is still very attractive and further developments are currently under way [18].

Temperature measurement methods based on heat radiation use infrared films, video-thermography, or total radiation pyrometry [2]. With the first two methods the temperature distribution can be determined by analyzing the degree of exposure of the film and the tube to the heat radiation. The latter is used to collect the total radiation of the measuring area with the aid of a lens system and focus it to an indicator. As a major advantage of these methods, modification of tool or workpiece is often not necessary, only optical access to the measuring area has to be guaranteed. Nevertheless, solutions with modified tools are also in use as shown in Figure 4.3-6 (bottom left) (see Section 3.3.3.3). The emission coefficients of the investigated materials are temperature dependent, and easier calibration is possible if the measurement is restricted to a single spot [3]. In Figure 4.3-8 results of measurements with an infrared camera using the single-spot method are shown. An interrupted cut comparable to milling is achieved by applying a workpiece with two strips at the circumference. The temperatures for different ceramic cutting tools increase with increasing cutting speed and with a change of the workpiece material from cast iron to steel. The same tendency was found with increasing feed.

Summarizing, it can be said that all systems are limited to application in the laboratory because of their complexity and the often necessary modification of components. The developed solutions have significantly supported the fundamental understanding of heat transfer in the cutting zone. However, the industrial use of any sensor as a means of process monitoring is not available.

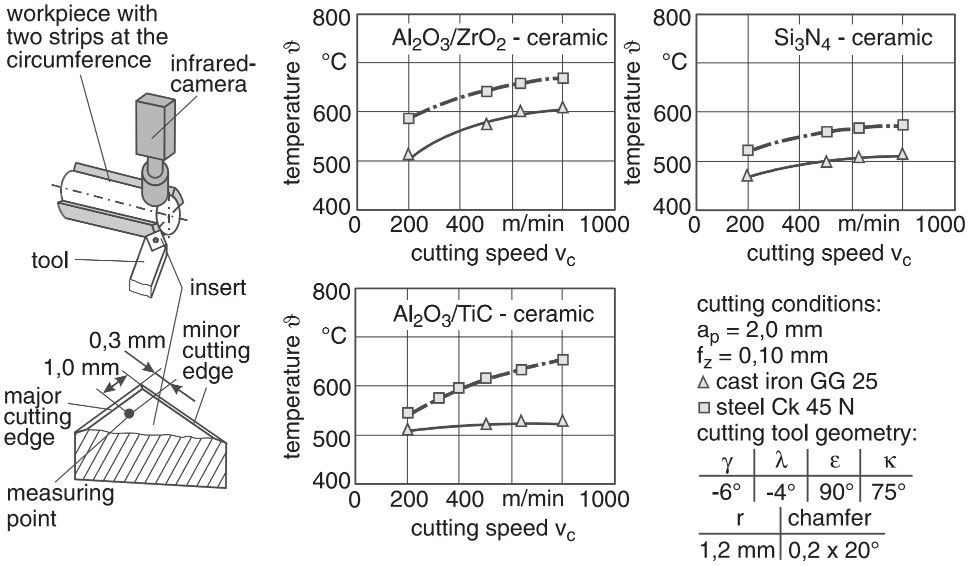

Fig. 4.3-8 Temperature measurement in interrupted cutting. Source: Denkena [3]

4.3.3.5 **Vibration Sensors**

The measurement of vibrations in machine structures can be done in two different ways. On the one hand, acceleration sensors are used which consist of a seismic mass and a spring-damping system connected with a displacement pickup. Often the piezoelectric effect of quartz is used to register the movement of the mass. The second solution is based on a relative displacement pick-up between two elements of a vibrating structure, eg, between the spindle and the housing on a milling machine [19]. The frequency range of these sensors is adapted to the type of phenomenon to be registered. Their application field is seen in the frequency range well below 150 kHz [1]. In other work the frequency range of vibration sensors was limited to 15 kHz [20]. In any case, these characteristics qualify vibration sensors also for tool condition monitoring. Acceleration sensors fulfil the demands of reliability and robustness, because they are designed for the use in rough environments. They can be easily applied to a machine tool component and do not need mounting very close to the zone of contact, because the frequencies to be detected do not suffer severe attenuation or distortion such as high frequency acoustic emission (AE) signals [21]. A pure mechanical sensor coupling is applied; small air gaps do not have a relevant influence. The terminology concerning vibration measurement is not clearly defined, and terms such as low-frequency acoustic emission [1] and ultrasonic vibration [21] are in use. In different publications the suitability of vibration sensors for cutting process monitoring was stated (eg, [19, 21]). Figure 4.3-9 shows a typical result of vibration analysis in turning [22]. The average amplitude spectra of a tool life cycle reveal clear differences between a new and a worn ceramic cutting insert. The vibration signal of a new tool is composed of low-frequency natural vibration modes of the lathe, the chip segmentation frequency at 34 kHz, and vibrations exceeding 50 kHz induced by friction and deformation. A change of the vibration pattern is visible after the

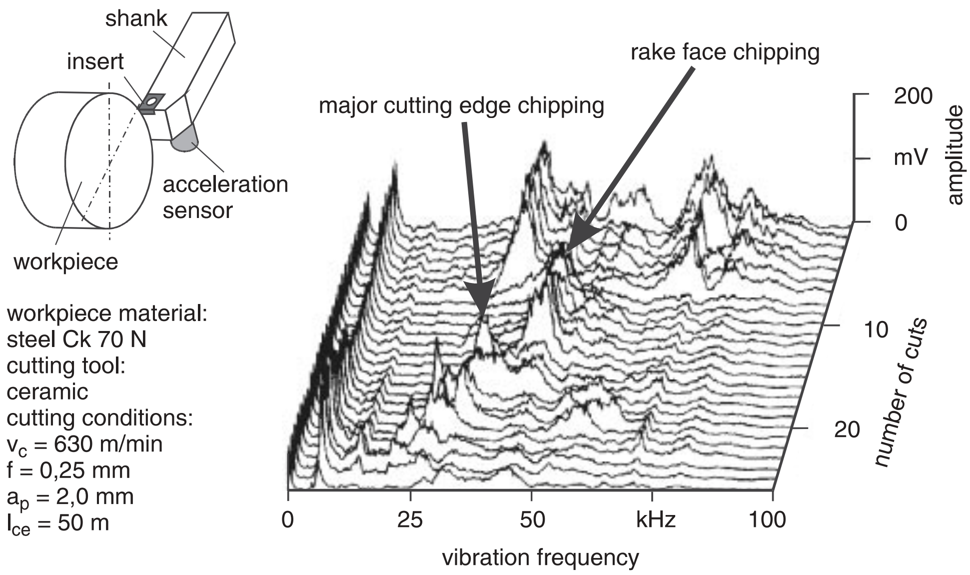

Fig. 4.3-9 Vibration amplitude spectrum change during turning of steel. Source: Warnecke and Bähre [22]

eighth cut owing to rake face chipping. The resulting increase in the rake angle shifts the chip segmentation frequency towards 45 kHz and reduces the amplitude in the frequency range 60–90 kHz. After cut No. 14 chipping at the major cutting edge is detected, leading to a quasi-chamfered edge geometry. The chip segmentation frequency decreases to 33 kHz. In the following cuts this segmentation frequency alternates owing to continuing chipping of the cutting tool. Finally, tool breakage occurs at the 26th cut.

This result proves the efficiency of vibration sensors in cutting processes. Owing to the mentioned advantages and the relatively low investment, they are very popular as monitoring devices. If frequencies above 100 kHz are to be investigated, the sensor system has to be changed to an AE sensor.

4.3.3.6 **Acoustic Emission Sensors**

AE sensors must be regarded as the most popular monitoring equipment in cutting processes over the last 20 years, despite force measurement. A large number of publications have dealt with the application and signal processing of AE systems. In a survey conducted in 1994, more than one fourth of 539 listed publications dealt with AE techniques in cutting processes [23]. The sources of AE signals have already been explained in Section 3.3. Basically two types of AE sensors have to be distinguished, wideband sensors and resonance systems. In the first case the sensor does not have a seismic mass to reduce an unwanted sensitivity in the low-frequency range. The sensitive element, most often piezoelectric based, is mechanically damped, sometimes by applying a relatively large damping mass. These sensors can be used up to the MHz range. The resonance type sensor has still a seismic mass and is in principle of the same type as an acceleration sensor.

The frequency range is limited owing to the design. An usual upper threshold is 250 kHz. If the measuring range is shifted to low frequencies in the region of 20 kHz, there is no clear difference from a vibration analysis (see Section 4.3.3.5). The coupling conditions are important; the signal transmission can be significantly improved by using grease in the gap between component surface and sensor. The sensor signals need further processing such as filtering, amplifying, and rectifying until the desired quantities can be deduced. Methods of artificial intelligence such as neural networks and fuzzy logic systems have also been applied to AE signals.

In most of the investigations on turning, the AE sensor is mounted on the tool shank, which is very close to the signal origin. For industrial application with the need for fast tool changes, this solution has some limitations. AE sensors are basically used to determine tool breakage and wear behavior. The first phenomenon will lead to a significant increase in AE energy. Many authors have used this clear signal for monitoring [1].

More complicated and challenging is the detection of tool wear using AE sensors because of two different effects. Increasing width of flank wear land increases the contact area between tool and workpiece and also leads to a temperature rise. On the one hand the energy of the friction-related acoustic waves increases, and on the other the shear strength of the workpiece material, shear angle, and contact length also change [10]. Hence a variation of the AE signal is likely to occur. In some publications an increase in bursts was reported, and rising root mean square values due to wear have also been published (eg, [24, 25]). Representative results of root mean square values during turning of steel with coated and uncoated tungsten carbide tools are shown in Figure 4.3-10 [25]. For uncoated tools a relatively low signal increase is visible over the very short tool life, while coated tools are much more suitable for this cutting operation and gen-

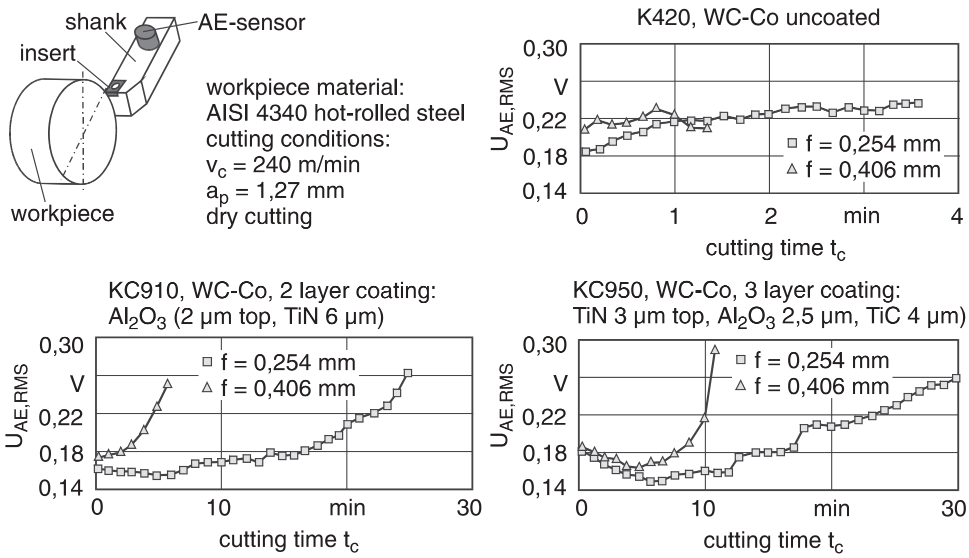

Fig. 4.3-10 AE-based tool wear determination during turning. Source: Cho and Komvopoulos [25]

erate a significant increase in the AE signal after the coating is worn. The initial problem of the r.m.s. value depends on the type of surface layer. The three-layer tool has a rough TiN top coating. During wear propagation of this layer, the signal decreases; after reaching the Al_2O_3 intermediate layer, an increase until total coating failure can be observed.

In [23], the peak position of the amplitude distribution curve of the AE signal, called AE mode, was proposed for improved identification of tool wear, because the influence of randomly appearing bursts is eliminated. Figure 4.3-11 shows representative results of this quantity and their determination procedure. The AE sensor was integrated in a modified tool shank and totally protected against coolant and other process residues. The AE mode values also show a clear increase with continuing flank wear. The nonlinear behavior is explained by the superposition of the effects of flank wear and crater wear. Whereas the former generates a clear AE signal increase due to the enlarged contact area, the latter leads to an increased effective rake angle, which reduces the AE activity. Finally, the flank wear dominates the signal with a further increase until large chipping of the tool occurs.

These two types of wear often occur at the same time. In [26], it was reported that the development of crater wear could totally compensate a further increase in the AE signal. In [27], even a decrease in the AE signal with increasing wear was observed. The choice of the frequency range for the AE analysis also has a major influence. As shown in Section 3.3.3.4 for surface integrity monitoring in hard turning it is possible to identify a narrow bandwidth of the AE signal for specific correlation purposes, where the signal also decreases with proceeding wear.

AE sensors have also been tested in a wide variety of milling experiments. The measuring task is more difficult because of the permanent change of chip thick-

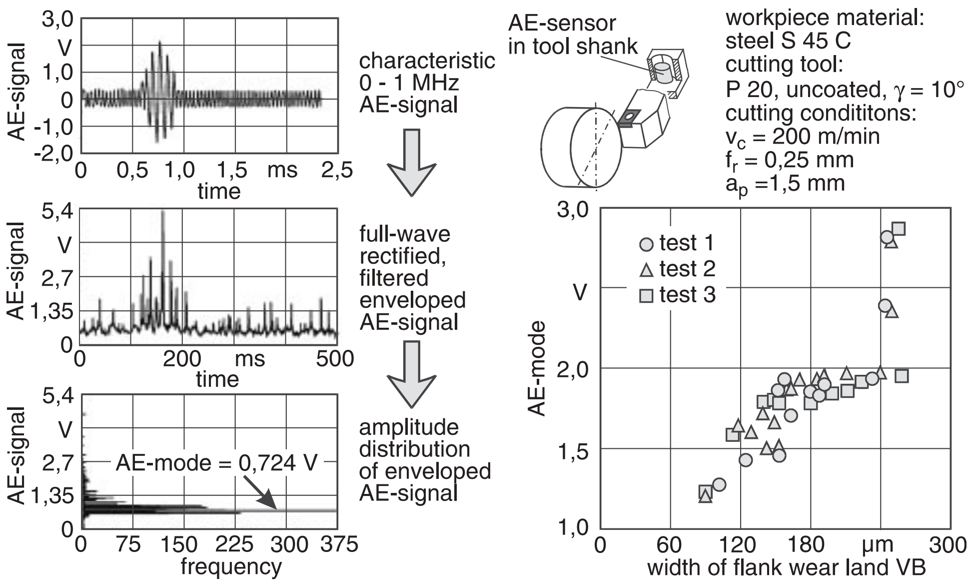

Fig. 4.3-11 Wear determination in turning with AE amplitude distribution analysis. Source: Blum and Inasaki [23]

ness and the pulses from the entrance and exit of the single cutting edges. Tool breakage leads to the same burst type increase of the AE activity as mentioned in turning. Different solutions for a suitable AE sensor position have been chosen. A mounting at the workpiece, at the rotating tool, under the insert, or by applying a special device at the spindle top for transmitting the signal through a magnetic liquid have been published. All these solutions have specific limitations for industrial use. In [10], a practical approach to establish an AE system for milling was made. Different sensors and mounting positions have been evaluated.

Figure 4.3-12 shows the result of the most suitable solution for tool breakage detection. A wideband AE sensor in the frequency range 100–500 kHz was mounted on the X-table of a horizontal milling machine, not influencing either the process or tool or workpiece change. The strategy is based on the application of dynamic thresholds. The problem is to separate tool breakage from disturbance signals. The upper part of Figure 4.3-12 shows the $U_{\mathrm{AE,\,RMS}}$ value together with the dynamic threshold. One real tool breakage and several other peaks are apparent. Two criteria are used to distinguish between these signals. The duration of exceeding the threshold is significantly larger for the tool breakage (6.2 ms) (Figure 4.3-12, middle) than for the disturbance peak (1.9 ms) (Figure 4.3-12, right). The shape of the pulse is described by signal differentiation (Figure 4.3-12, bottom). The disturbance peak shows only one oscillation, whereas the breakage signal oscillates over a longer period. The proposed tool breakage monitoring system has to check both criteria, exceeding time and differential signal shape, to trigger an alarm signal [10].

Again, the determination of wear influence on the AE signal in milling is more complicated. In [28], results of experiments on a vertical milling machine during single- and multi-tooth face milling of steel are presented. The influence of different input quantities was evaluated. Wear could only be determined during single-

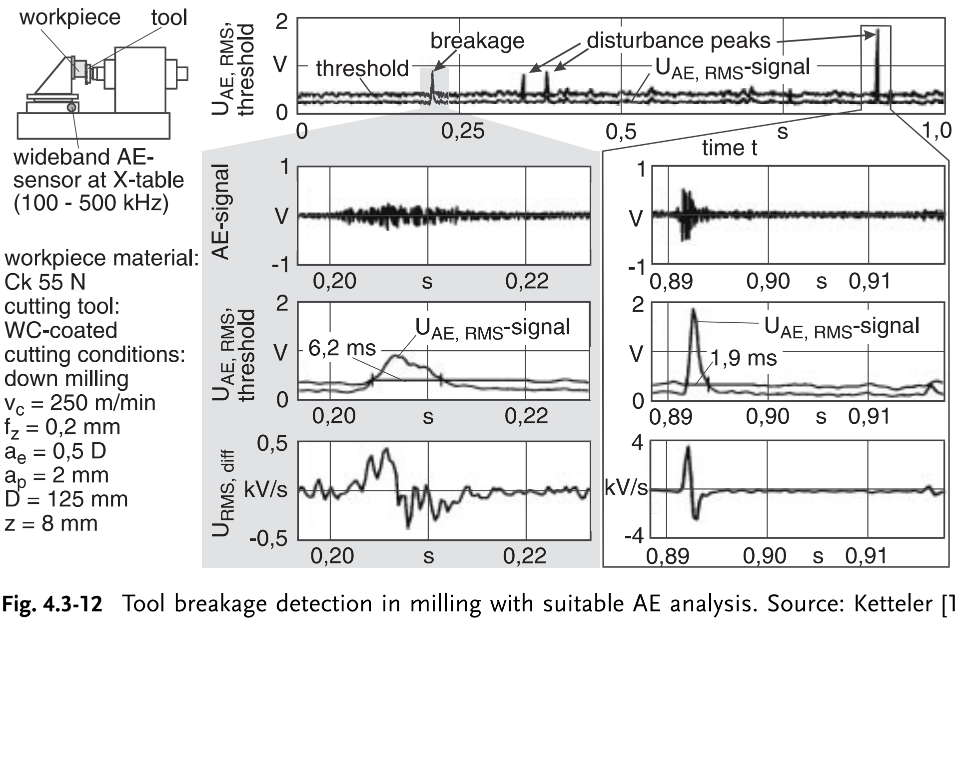

Fig. 4.3-12 Tool breakage detection in milling with suitable AE analysis. Source: Ketteler [10]

tooth milling, where a fluctuating increase in the root mean square value was found with proceeding wear. A contrary tendency of wear and the AE root mean square value were reported in [29] for cutting speeds above 220 m/min. The same decrease of $U_{\mathrm{AE,\,RMS}}$ with rising tool wear was reported in [30] during face milling of steel at a cutting speed of 300 m/min, using a special type of fiber-optic interferometer for acoustic emission measurement. Kettler used a resonance-type sensor in the lower frequency range of 20–100 kHz for the determination of tool wear [10]. In Figure 4.3-13, results of his investigation are shown. The sensor is mounted on the pallet of the workpiece. The major problem for this measurement is the occurrence of additional, not directly wear-related AE sources such as chip contact, chip breakage, or burr formation. By analyzing the AE signal in the lower frequency range of the resonance-type sensor, it is possible to suppress these influences and to identify single teeth of the tool. The root mean square value $U_{\mathrm{AE,\,RMS}}$ increases with proceeding wear over the cutting length. Teeth 7 and 8 have major cutting edge chipping at the highest cutting length of 45 m, whereas the maximum width of flank wear land for tooth 1 is 0.4 mm at this stage. In this investigation, the average of the root mean square value was found to be most suitable for wear characterization.

The discussed results reveal that the AE signal also has good potential for milling process monitoring. Although tool breakage detection is relatively easy to achieve, further work has to be done for wear determination, especially for processes with coated cutting inserts because of their complex wear behavior. The contradictions of AE activity and wear behavior are not yet fully understood. Further research is necessary until robust systems for industrial use are available.

It should be mentioned that AE sensors have also been applied to many other processes with geometrically well-defined cutting edges. Publications on drilling [31], reaming [32], deburring [33], tapping [34], and planing [35] are available. The

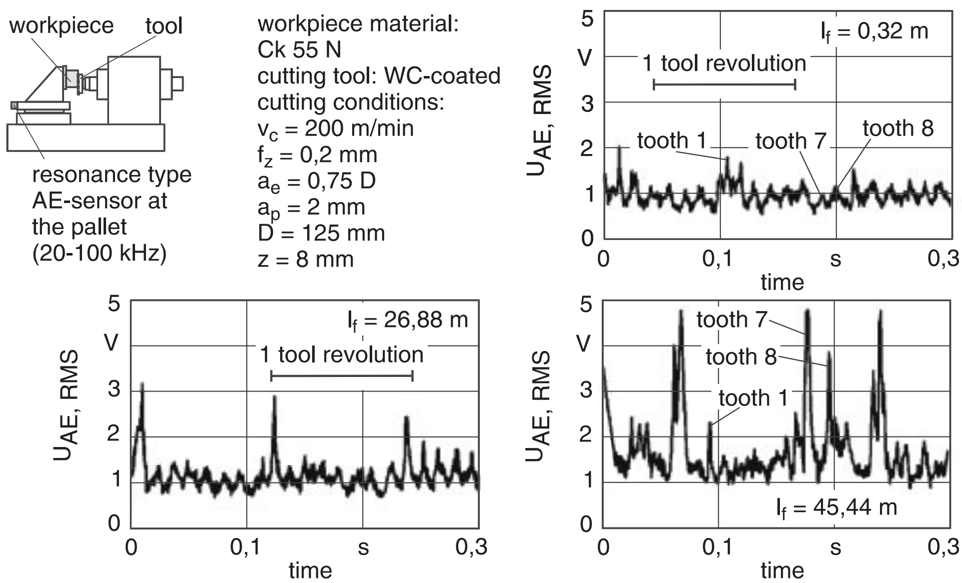

Fig. 4.3-13 Tool wear detection with acoustic emission during milling. Source: Kettler [10]

basic principles of sensor application, signal processing, and evaluation strategies can be compared with the mentioned systems.

Summarizing the potential of AE, it can be clearly stated that these sensors offer a wide range of interesting applications. Almost any phenomenon can be detected, at least in the laboratory. Future should be concentrated on systems applicable to the rough environment of cutting processes without hindering the process or changing procedures and on robust and fast algorithms to allow on-line decisions and to avoid false diagnosis.

4.3.4
Tool Sensors

All sensor systems which are directly related to the tool try to obtain information about the geometric features of the cutting edge. As already explained, every tool is assumed to wear owing to the occurrence of thermal, mechanical, and in certain cases also chemical load. Based on these loads, typical different mechanisms of wear are present such as abrasive, adhesive, diffusive, and oxidation wear, as well as crack formation and breakage [2]. These mechanisms result in different wear forms, the most important ones being found on the rake and flank face, such as width of flank wear land VB or crater depth. These quantities can be determined during laboratory investigations by removing the tool from the machine at specific intervals to be checked by microscope or stylus measurements. The purpose of any tool sensor is to determine these or similar quantities in the working space of the machine tool; the optimum solution would be a direct measurement during cutting.

In Figure 4.3-14, an overview of the most important methods is given. The solutions presented comprise sensor systems for both stationary objects and rotating

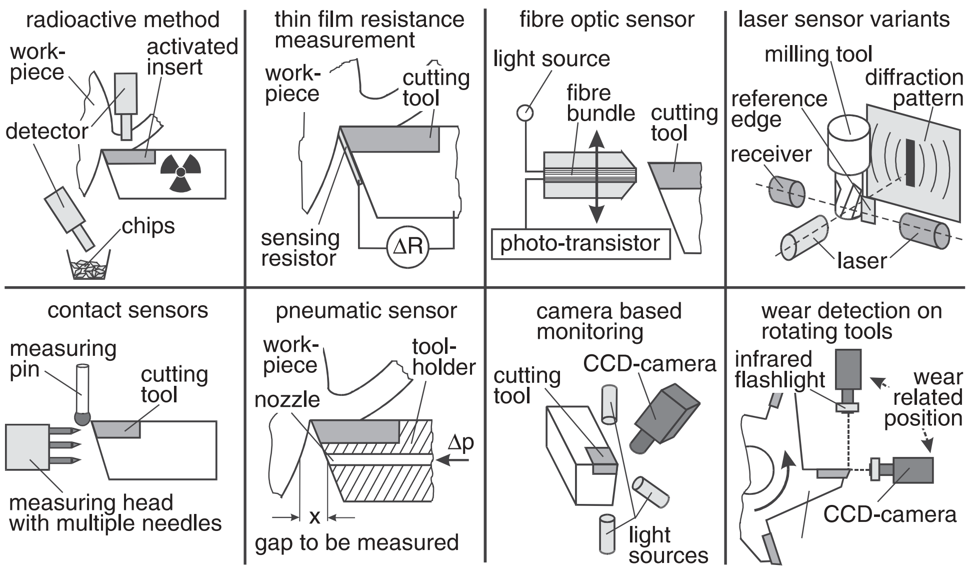

Fig. 4.3-14 Sensors for tool measurement during cutting

tools. In the early days of cutting research one of the favorite methods was to use radioactive cutting tools for tool-life testing. The tool was activated by irradiation. Worn tool material, which was transferred to the chips, was monitored by collecting the chips and measuring their radioactivity or by determination of the remaining radioactivity of the tool with a suitable detector. Although at least in later applications of this method the radioactivity was very small, this method could not achieve practical importance owing to the dangers with any kind of radioactivity, the necessity for irradiation facilities, and the limited sensitivity under specific conditions. Attempts were also made to use chemical analysis for fast tool-life testing by pickling the chips after 1 min cutting to analyze the residues with respect to tool material tracing [36]. However, the chemical efforts incorporating a calorimetric analysis were not practical.

Contact sensors of different kinds have reached practical application because of their low investment, robust design, and relatively easy integration and signal evaluation. Measuring pins with wide geometric variations are available and have been used in lathes and milling machines. In most cases the purpose is to determine the displacement of the cutting edge in the face direction, because any change in this dimension directly influences the geometric accuracy of the machined part. By measuring its cutting edge displacement, the depth setting of the tool can be adjusted to maintain the desired workpiece diameter. A contacting measurement of the width of flank wear land in the machine tool was also tried by using a measuring head with several contacting needles (Figure 4.3-14, bottom left). Although the resolution was sufficient with 10 μm, systems of this type could not achieve wider acceptance mainly because of the time and space demands in the machine tool.

The use of thin-film sensors was proposed to measure the wear of the flank face (Figure 4.3-14, top middle-left) [37]. The material was printed on the flank face, insulated by a heat-resistant paint and exposed to continuing wear. The length decrease of the thin film due to the increase in the width of flank wear land was registered via resistance measurement. This interesting idea of thin-film sensors on tool surfaces was further developed to measure temperatures directly (see Section 4.3.3.4).

Pneumatic sensors are used to determine the displacement of the cutting edge in the face direction by measuring the gap between the tool holder and the generated workpiece surface (Figure 4.3-14, bottom middle-left). The sensor is based on the nozzle-bounce plate principle. The nozzle is integrated in the tool holder and the pressure change in dependence of the gap width is measured. The set-up is simple, the measuring range was around 400 μm, and an accuracy of 2–3 μm could be achieved. However, variations in temperature, pressure, and surface quality have some influence on the reliability and sensitivity of the sensor.

Apart from these mentioned sensor systems, most solutions are based on optical measurement. One of the first attempts was a sensor based on fiber optics to measure the width of flank wear land (Figure 4.3-14, top middle-right). One half of the fiber bundle illuminates the flank face of the tool and the reflected light is registered by the other half. The displacement of the cutting edge has to be taken into account, because the light intensity decreases with larger distances. An accuracy of 10 μm was reported.

The consequent next step was to use a charge coupled device (CCD) camera for measuring the cutting edge geometry [37, 38] (Figure 4.3-14, bottom middle-right). The features of the camera itself are most often very similar. The sensitivity of the approach is directly related to the quality of the lightning. Fiber optics with additional equipment to diffuse the light or a laser light source with a diffraction grating is one of the applied methods. With additional movement of the camera and the lightning, separate analyses of flank wear and crater wear are possible. If the system is integrated in the working space of the machine tool, it is, of course, only possible to measure the cutting edge geometry in auxiliary times. The measuring time, space demand, and protection efforts to cover the system during cutting operations under coolant supply are still limiting factors for wider application. Outside the machine tool these systems have already had a considerable impact. A complete 3D analysis of a cutting insert is possible by applying projected fringes to the tool surface and using a CCD camera with adapted software [38]. The most complex optical system for cutting tools is shown schematically in Figure 4.3-15. The measuring machine is built to determine automatically all relevant geometric data on rotational cutting tools such as milling cutters. The machine has a four-axis CNC control to focus the optical system on every part of the tool of interest. With a combination of two CCD cameras, one working in the direct illumination mode and the other with transillumination, it is possible to determine the whole complex geometry of the tool. A very important feature is the lightning system with a special light-emitting diode (LED) array, which allows control of the light intensity of different diode sections individually. The machine was originally designed as a measuring machine in combination with a six-axis CNC tool grinding machine to generate automatically the NC program of the grinding operation after tool measurement especially for re-grinding of worn tools.

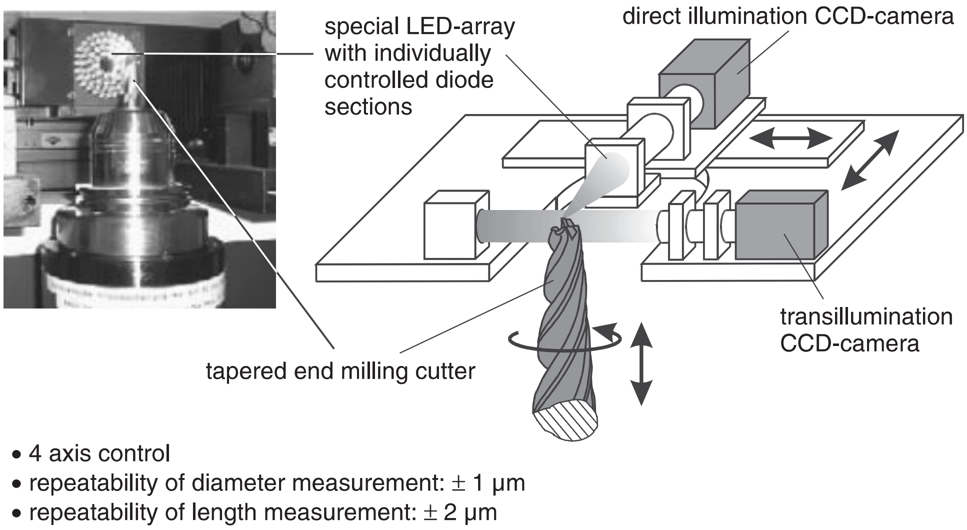

Fig. 4.3-15 Optical measurement of the total geometry of rotary tools. Source: Walter-Vialog AG, Hannover

However, the very precise determination of tool wear of any kind with this system is a clear motivation to extend the application field. Integration in the working space of the machine tool is not possible, but an implementation in the tool magazine seems to be very promising. Initial studies have already been made; with a further decrease in the system costs by reducing the accuracy demands of currently 2 μm to more practical values, a realistic return of investment can be achieved in a very short time.

For milling operations, a measurement of the rotating tool would be the best achievable solution. Several attempts have already been made, all based on optical methods. In [39] it was proposed to use the diffraction pattern of laser light, which is sent to a small slit between the rotating tool and a reference edge (Figure 4.3-14, top right). Flank wear states between 0.2 and 0.4 mm could be distinguished by analyzing the fringe pattern, but the major drawback is the extreme importance of the exact and repeatable positioning of the tool at the reference cutting edge, because this directly influences the result.

A solution which has already been introduced to practical application is the use of a laser light barrier in the working space of a milling machine tool. The purpose of this method is to determine the envelope curve of the rotating tool in order to adapt the process parameters to the individual length or diameter and to identify tool breakage. In Figure 4.3-16 some results of investigations in a state-of-the-art milling machine tool are shown.

It can be seen that the accuracy of the measurement is directly related to the approach speed. Every pass through the light barrier generates a trigger signal for the control of the machine. The second and third approaches are made with significantly reduced speed. The length and diameter determination is done by reading the machine tool axis data after passing through the light barrier. Hence the

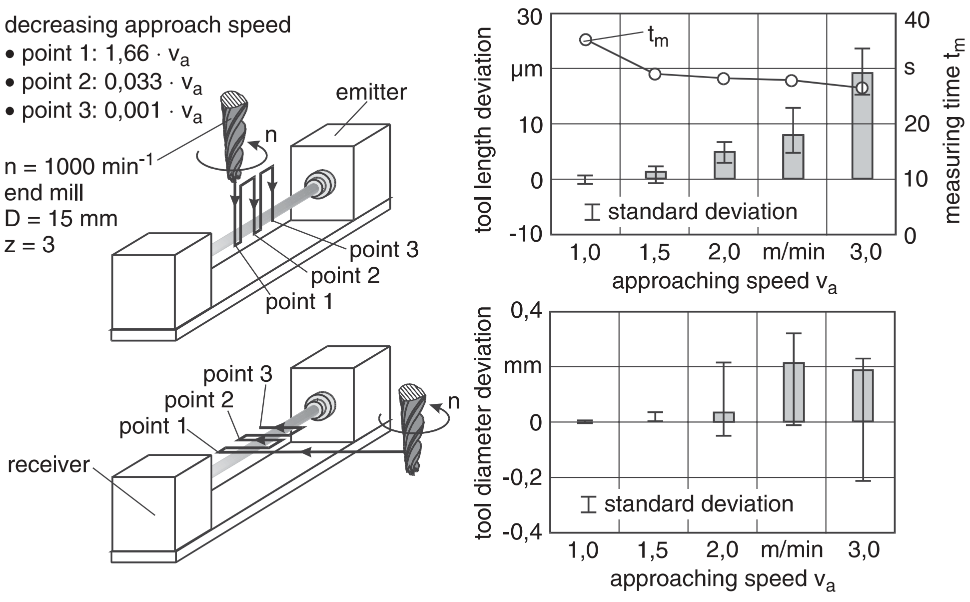

Fig. 4.3-16 Tool measurement in a milling machine with a laser light barrier

precision of the measurement is dependent on the machine tool accuracy and the processing speed of the trigger signal. In the investigated case with an unknown tool and a measuring cycle with three transits through the light barrier, a measuring time of approximately 30 s is necessary; an increase in the approach speed has only a negative influence on the accuracy and will not reduce the time considerably. The achievable accuracy is sufficient for most practical applications and is comparable to that of external tool pre-set techniques. Mechanical shutters during cutting can protect the system. The importance of this sensor type will increase further with the capability of modern milling machine controls to effect automated radius compensation of the NC program with decreasing tool diameter due to wear or re-grinding before re-coating.

A different approach was chosen in [40]. Based on a laser sensor, both displacement and intensity techniques are applied to determine the wear of a milling cutter.

The whole set-up is mounted on the main spindle and able to measure even during tool rotation (Figure 4.3-17). On the right, results of displacement and intensity signals for three different tool wear states are presented. The chipping of the tool and the length of flank wear could be determined to an accuracy of 40 μm. Even the first attempts to measure during face milling under coolant are reported. Applying a special compensation method could drastically reduce the influence of coolant and chips on the measurement. Furthermore, a 3D reconstruction of the tool based on the laser sensor signals is possible. This method seems to have a high potential for further development. Because of the massive reduction of flexibility and increased danger of collision, application on the main spindle is possible only for laboratory investigations. However, a sensor application in the workspace of the machine tool for intermittent fast measurement will be much more acceptable.

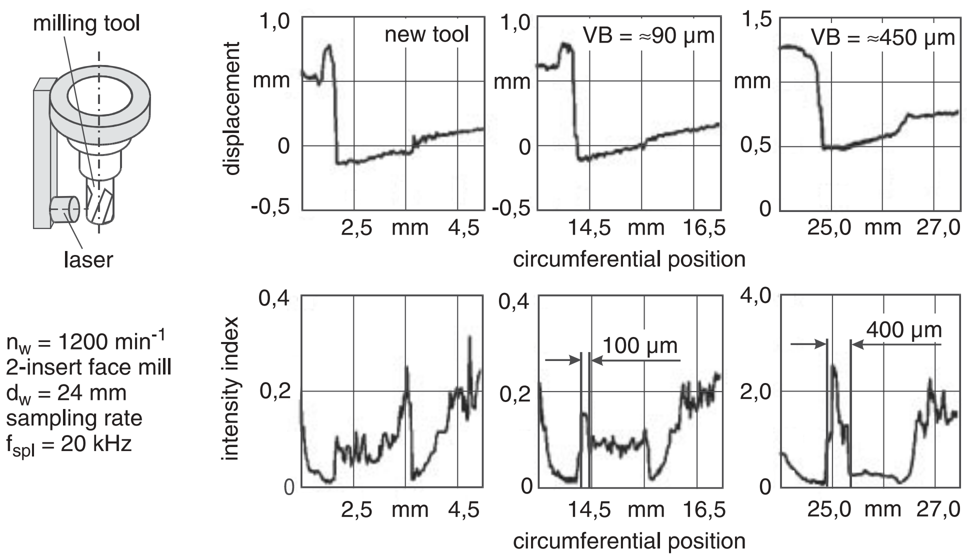

Fig. 4.3-17 Laser sensor for wear determination during rotation of milling tools. Source: Ryabov et al. [40]

The last optical method to be mentioned is based on a CCD camera with a special circular infrared flashlight [41] (Figure 4.3-14, bottom right). With this equipment it is possible to measure flank wear of individual inserts during rotation of the milling cutter at 750 min^{-1}. By shifting the camera to a top view position of the rake face, crater wear should also be detectable. The idea of increasing the measuring speed by using a high-speed flashlight has further potential, but it is expected to remain a technique for laboratory investigations.

Summarizing the discussed sensor systems for tool measurement, it can be said that contacting pins and laser barrier techniques have already reached industrial maturity. The application of any kind of complex optical sensors such as CCD cameras will remain a problem owing to the rough conditions in the working space of a machine tool, but future integration in the tool magazine seems to be very promising even under industrial conditions.

4.3.5 Workpiece Sensors

The measurement of the workpiece quality during cutting processes is in most cases related to geometric features. Sensors for physical properties to determine the surface integrity state are very rare and have already been discussed in Section 3.3. The geometric quantities can be further divided into macro- and micro-geometry (see also Section 4.4.5). The numbers of sensor systems and applications and published results are not as large as for abrasive processes. The main reason is the reduced accuracy demand on cutting operations compared with abrasive processes, which are mostly applied for finishing. Nevertheless, different sensors have been used during turning and milling and will be discussed. The sensors

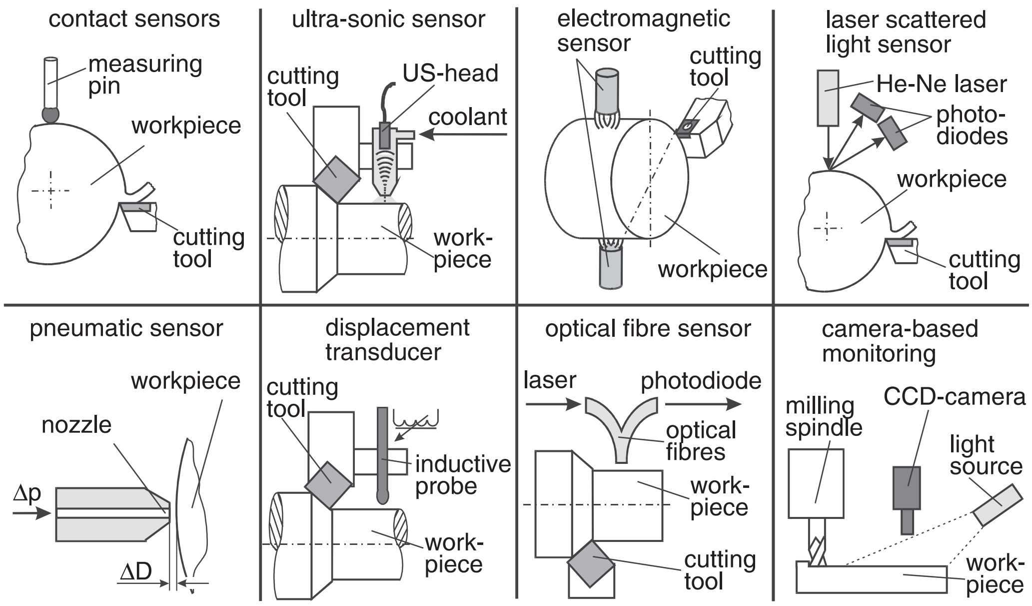

Fig. 4.3-18 Workpiece sensors applied to cutting processes

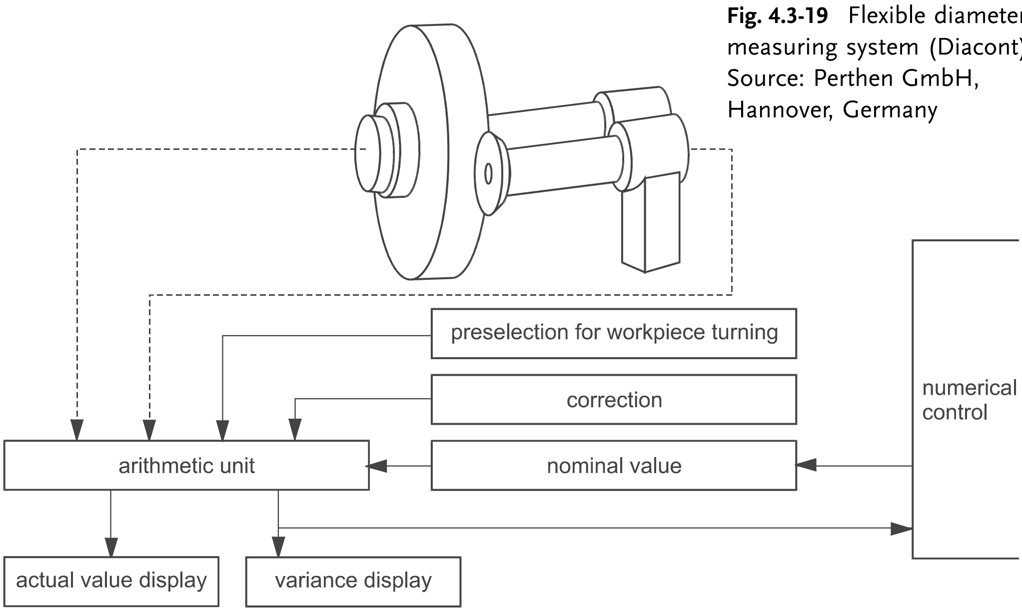

Fig. 4.3-19 Flexible diameter measuring system (Diacont). Source: Perthen GmbH, Hannover, Germany

used for macro-geometric quantities are mostly of the contact kind (Figure 4.3-18, top left), mainly applied before or after the machining process.

Pin-shaped sensors are applied to both rotational and for prismatic parts. Usually, these devices use the measuring and positioning system of a numerical machine. Therefore, they do not work independently. Figure 4.3-19 shows a contact sensor which measures absolutely.

It returns the diameter measurement to the determination of the circumference by comparing the number of rotations of a contact roller with the known diameter and the number of rotations of the workpiece to be measured. This sensor can be applied during operation on outer and inner diameters and its application is therefore very flexible. Problems are the unavoidable slip, the elastic deformations of the contacting bodies, and their dependence of the workpiece roughness. This means that the measuring accuracy is limited. Nevertheless, the sensor is successfully used in practice for the measurement of large diameters.

Quality control after machining and an initial measurement of the workpiece geometric orientation in the working space of a machine tool before cutting are possible. During turning an in-process measurement is also used; in this case a size deviation of the workpiece due to displacement of the cutting edge will be recognized in order to conduct a further cut or to remove the tool. Pneumatic sensors are also in use. The principle is the same as already explained in the previous section. The only difference is that the air supply is not passed through the tool holder. An independent sensor is mounted on the opposite side of the cutting tool. Again, it is the purpose to measure size deviations and to register cutting edge displacement.

The same geometric information can also be achieved by applying an ultrasonic sensor to determine the distance between the cutting tool and the workpiece (Figure 4.3-18, top middle-left). The signal coupling is done via coolant, which flows around the ultrasonic head to the workpiece surface. This technique can be used for cutting speeds up to 200 m/min; a further increase will lead to breakdown of the fluid coupling. The idea of ultrasonic surface testing was taken up again and extended from the determination of macro-geometric quantities to surface roughness measurement. First a post-process measurement with the workpiece placed in an immersion tank was applied. Further development allowed on-line measurement via coolant coupling in the chosen milling machine [42]. The sensor was mounted on the spindle housing and the measurement was performed at the chosen table speed. This technique is not negatively influenced by coolant as in all optical methods, remaining chips on the surface being washed away by the coolant flow. However, the major problem is to keep the coolant clean and bubble-free, because any change in the coupling conditions will have a significant influence on the measurement result. Nevertheless, these initial results seem to be promising and further research is under way to improve the system performance and reliability.

Displacement transducers are one further possibility to determine a change in the tool-workpiece distance during turning operations due to cutting edge displacement or chatter vibrations (Figure 4.3-18, bottom middle-left). Both in hard turning and in precision machining, inductive-based displacement sensors have been used to determine the vibrations during turning.

Electromagnetic sensors on conductive materials can monitor the change in the workpiece diameter (Figure 4.3-18, top middle-right). In [43] a sensor based on this principle was applied during turning to deduce tool wear from the diameter change. The two sensors were set up in a differential mode to compensate vibrations and deflections. The gap between workpiece and sensor should be in the range 0.5–2.2 mm for optimum sensitivity. Diameter changes of 7 μm could be detected at a cutting speed of 170 m/min, but it was not possible to distinguish between nose wear and flank wear.

The following techniques are all related to optical methods. The use of fiber optics is one of the favorite methods for guiding appropriate lightning to the workpiece surface and for registering the reflected light (Figure 4.3-18, bottom middle-right). In [44], a sensor based on fiber optics was used to measure the surface profiles of milled workpieces. By evaluating the waviness of the machined surfaces, the development of tool wear could be estimated. In [45] the reflectance of a turned surface was measured in-process with a fiber-optic sensor. With additional use of a neural network, the tool wear state could be deduced from the optical results.

Figure 4.3-18 (top right) shows a set-up with an He-Ne laser as light source for roughness measurement during turning. The inclining laser beam can be split to give information in the feed direction of the cut. Results from in-process application revealed that it is possible to determine the peak-to-valley height of the workpiece during turning with acceptable accuracy, but chipping of the tool and chatter vibrations increased the deviations from a post-process reference measurement.

Further solutions are based on the application of cameras. Either in turning or in milling CCD cameras have been applied to determine the topographical state of the machined surface. While the significance of optical parameters was first investigated in the laboratory, the cameras were then moved into the working space of the machine tool. The major problem with this approach is that increasing tool wear does not always lead to a deterioration of the surface quality. A severely worn tool can produce a better surface quality than a new tool. Of course, a correlation of optical parameters with stylus roughness quantities could be found. At least the standard deviation of the gray level distribution could indicate increasing wear.

In [46], the CCD camera was integrated in a milling machine to measure the generated surface on-line (Figure 4.3-18, bottom-right). As a special feature, an area-based fractal approach was chosen to describe the roughness state. After a necessary calibration a good correlation between the fractal dimension and the standardized roughness quantities could be achieved. Limiting factors are the restriction to dry machining and the finite speed of the frame grabber. However, also a fast post-process area measurement of the roughness distribution is of great interest for industrial applications.

The last optical method to be mentioned is the use of high-speed cameras. This technique, also known as micro-cinematography, has been used in fundamental investigations to visualize the chip formation (eg, [47]). With major technical effort incorporating a hollow spindle for the camera access and an etched workpiece pressed to a quartz glass window, it is possible to monitor continuously the material behavior in the shear zone during orthogonal cutting. The created movies contributed substantially to a better understanding of the procedures during the tool-workpiece interaction.

Summarizing the sensor solutions for workpiece measurement, it can be said that currently only sensors based on workpiece contact have found wide acceptance in industry. All other mentioned solutions have either specific limitations or were definitely developed for fundamental research. Optical methods will always have problems with coolant and process residues during on-line measurement, but offer a wide range of fast and increasingly reliable solutions for post-process measurement in the machine tool surrounding. Ultrasonic sensors do not suffer from these problems in the same way and may therefore gain more importance in the future.

4.3.6
Chip Control Sensors

The type of chip removal directly influences the result of any cutting operation. Thus monitoring of the chips and their breaking and removal has been the subject of many investigations. Although the chips are part of the workpiece material and monitoring is possible only during the process, sensors for this purpose will be mentioned separately in this section. Figure 4.3-20 gives an overview of the most popular solutions for chip monitoring. Many researchers try to use an already installed sensor system also for this special purpose. Thus piezoelectric dynamometers and AE sensors are employed for chip breakage detection (Figure 4.3-20, left). The sensor mounting and signal processing do not differ significantly from those in the previous mentioned applications.

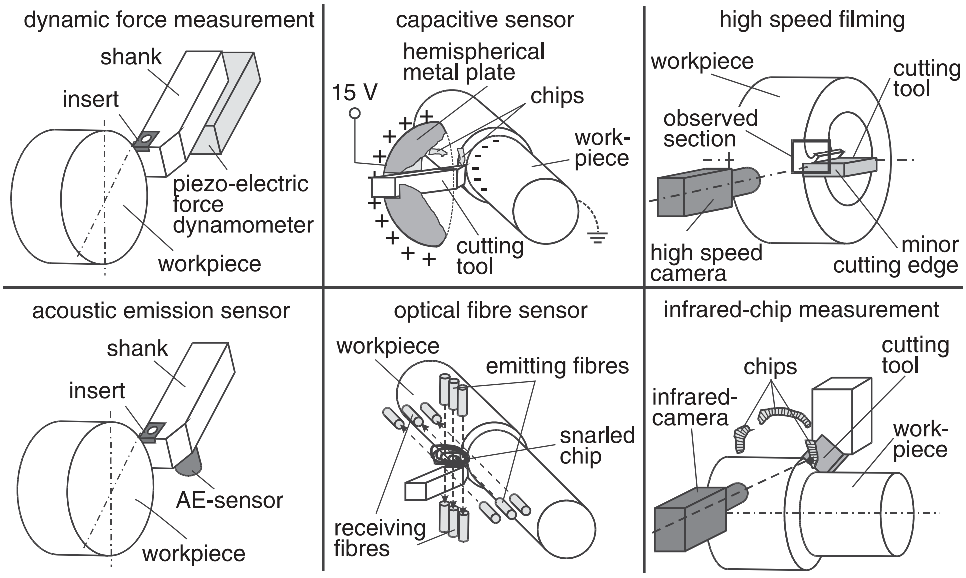

Fig. 4.3-20 Sensors for chip monitoring during cutting processes

During force measurement, the strategy is based on the evaluation of the dynamic components of the force signal (eg, [48]). However, this method has specific frequency limitations. Especially for high-speed cutting with high chip lamination frequencies, force-based chip monitoring is not possible. As explained, AE sensors offer a suitable range of frequency sensitivity and are thus used for chip-form detection. However, with the availability of AE signals from the process, most authors concentrate on directly correlating them with tool wear.

A different approach is based on the use of a capacitive sensor [49]. Venuvinod and Djordjevich formed a capacitor from a hemispherical metal plate and the corresponding part of the metallic workpiece (Figure 4.3-20, top middle). A fixed potential of 15 V is applied on the plate and the machine is grounded. The tool itself has to be isolated from the plate to prevent continuous discharge. During cutting, every chip is electrically charged and likely to collide with the plate. This contact will generate a small discharge and only applying an additional charge can restore the initial potential. This is done by electric current, and the registered current peak is related to the size of the contacting chip. Geometric information such as chip thickness cannot be derived; the major task is to register continuous chips or chip entanglement, which would lead to a total discharge of the capacitor [49].

Using optical fibers can also solve this problem. With a rectangular arrangement of emitting and receiving fibers it is possible to detect the occurrence of chip entanglement [49] (Figure 4.3-20, bottom middle). A distinction between flying broken chips, which will also cause an interruption in the light transmission, and snarled chips is made by time considerations. The distance between emitter and receiver can amount to 30 cm, but still the installation in the working space of a machine tool does not seem to be possible for practical applications.

Figure 4.3-20 (top right) shows an often-used set-up for fundamental investigations concerning chip formation. A high-speed camera is applied to monitor the

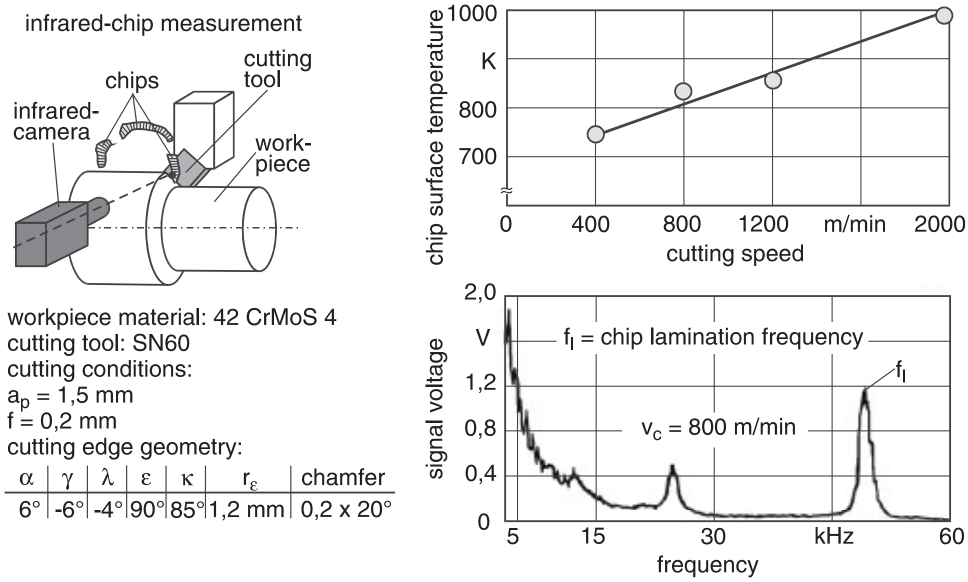

Fig. 4.3-21 Chip temperature monitoring during turning with an infrared camera. Source: Winkler [47]

cutting process, which is often restricted to orthogonal cutting (eg, [48]). Single pictures of the observed section reveal the mechanisms of chip formation. High-speed cameras are also suitable for monitoring turning operations with interrupted cut on workpieces with stripes as a simulation of milling [10].

A technique based on heat radiation is also suitable to obtain information about the chips (Figure 4.3-20, bottom right). In [47] an infrared camera was used to determine the temperature on the chip surface at different cutting speeds and to gain access to the chip lamination frequency by directly computing the temperature signal in the time domain (Figure 4.3-21). The results reveal a rise of the chip surface temperature with increasing cutting speed, because the heat generated has no time to penetrate into either the workpiece or tool. It is concentrated in the shear zone and removed with the chips. By applying a special signal processing it is possible to determine the chip lamination frequency, which is around 48 kHz for the chosen conditions at a cutting speed of 800 m/min.

Further, it should be mentioned that ultrasonic techniques and thermocouples have also been used to obtain information about the chip contact length and chip formation.

All the presented sensor solutions except AE systems are not really suitable for industrial application. Their purpose is to increase the fundamental knowledge about chip formation and to help toolmakers in the design of new cutting tool geometries. With the fast-developing computer software and hardware they can also contribute to calibrate simulation programs for chip forming by quantifying the effect of different calculated design developments.

4.3.7
Adaptive Control Systems

With the introduction of computer-based machine tool control units, the rapid development of adaptive control (AC) systems also took place. The major purpose of any AC system is to maintain the desired workpiece quality over a long period of manufacturing time and to increase productivity. Pre-set parameters are transmitted to the CNC machine tool control and transferred to setting quantities for the process such as feed, speeds, etc. The process is exposed to additional disturbing quantities, which may influence the output. With the application of sensor systems for the monitoring of both output quantities and process quantities, it is possible to adjust the setting quantities to any change during operation of the machine tool. This measurement of a quantity deduced from the machining operation to be held on a defined level in a control loop is called adaptive control (Figure 4.3-22).

The approach to operate cutting processes in a desired condition by controlling machining parameters according to the measurement of process or output quantities can be further divided into the two following cases:

- Adaptive control constraint (ACC). The chosen process quantity is not allowed to exceed a *fixed limit* value. Even under the influence of disturbing factors such as changing workpiece material characteristics or tool wear, this limit will be approached as close as possible without exceeding the given maximum value of the setting quantity (eg, the feed). Usually the regulating quantity in such a system is a process quantity.
- Adaptive control optimization (ACO). Based on a chosen strategy the process is conducted to reach a *desired optimum value*. This optimum has to be defined, eg, it can be either the achieved workpiece quality or the machining time. This type of system can be operated with both process and output quantities. The

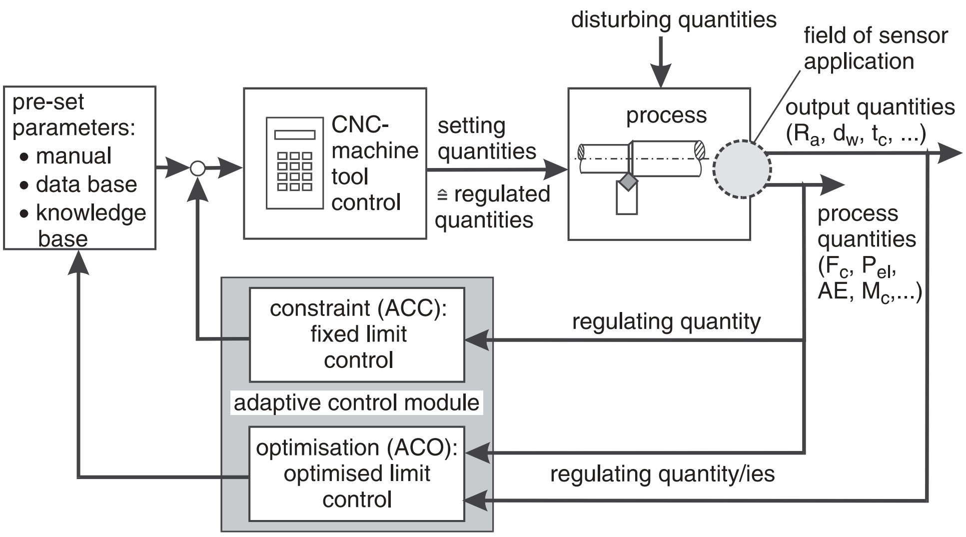

Fig. 4.3-22 Schematic set-up of adaptive control systems

most complex ACO systems not only regulate the setting quantities through the CNC unit, but will also modify the pre-set parameters if necessary. In principle, an ACO system should provide a better performance than an ACC system.

To visualize the effect of AC application for cutting processes, the advantages are shown schematically in Figure 4.3-23.

In conventional machining without AC use, the feed has to be fixed on the basis of the most difficult operation to be expected on the corresponding workpiece. The application of AC allows the setting quantities to be modified according to the actual cutting conditions. Thus in the case shown, changing depth of cut, different material properties, air gaps, and tool wear will lead to an adjustment of the feed either for turning or milling operations. From this very general approach it is evident that the major application field for AC systems in cutting is the roughing process. A change of the feed influences the surface topography and corresponding roughness values and might not be allowed in several cases. Any modification is only possible, of course, if the change in cutting conditions is detected with suitable sensors. In addition to the distinction between ACC and ACO systems, there is also a difference between geometric and technological AC systems. The first group is based on the measurement of basically macro-geometric quantities of the workpiece, whereas the latter uses process quantities to achieve the best possible productivity. All sensors which have been tested for AC systems in cutting have already been explained in previous sections.

In geometric AC systems for turning pneumatic sensors, inductive displacement probes and optical sensors were applied to measure the workpiece diameter (eg, [50, 51]). Technologically oriented AC systems are often based on cutting force measurement either by strain gages or piezoelectric dynamometers. Further-

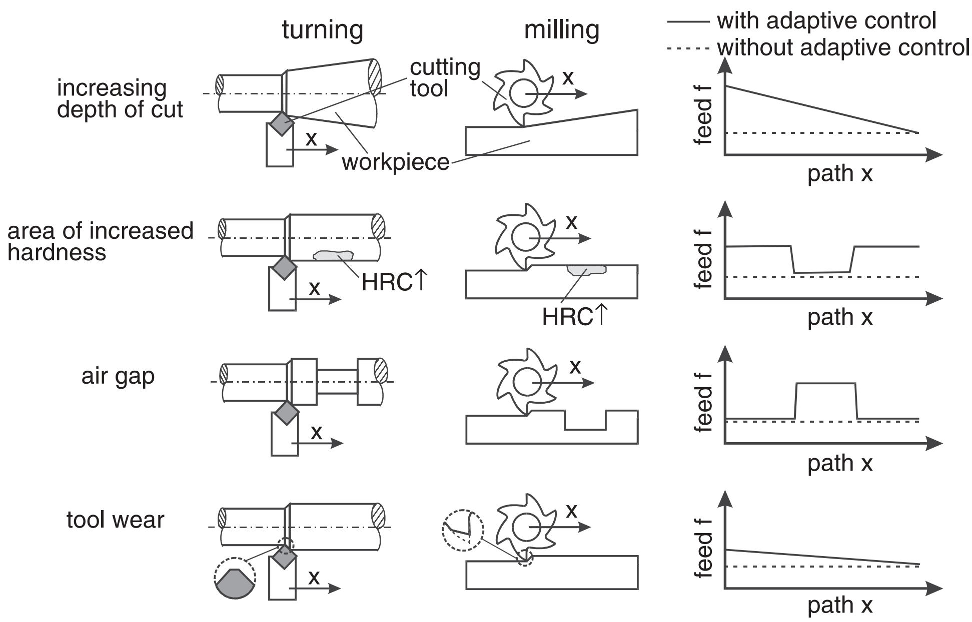

Fig. 4.3-23 Productivity improvement by adaptive control in cutting processes

more, chatter detection by force, torque, or acceleration measurement was included in AC systems. Systems for wear detection have also been tested based on pneumatic, ultrasonic or thin-film resistance sensors, but could not achieve practical importance. Motor power or current monitoring is another opportunity to establish an AC system, but special attention has to be paid to the influence of temperature. The main features of these AC systems for turning incorporate a strategy to allow idle paths at rapid feed to reduce the overall machining time, automated distribution of cutting paths, and tool life monitoring [50]. With the introduction of CAD-based machine tool programming, some of the described features lost their importance. Nowadays the determination of tool wear and breakage and chatter detection are the main monitoring tasks of sensors. Their signals are fed back to the control unit of the lathe in the sense of an AC system to reach the desired process condition and workpiece quality.

The development of AC systems for milling processes is characterized by the higher complexity of the process with rotating tools consisting of multiple cutting edges and changing chip thickness. Developments also started more than 30 years ago. Systems based on strain gages in the spindle for torque monitoring, spindle deflection measurement by displacement sensors, vibration sensors, motor power consumption or force measurement, as well as AE sensors have been applied to AC systems. In most cases the feed or feed speed is the regulated quantity; during chatter detection, a reduction of the depth of cut can also be chosen. Furthermore, in some cases the rotational speed of the spindle was adjusted. The basic features of the first-developed AC systems for milling incorporated a contact detection procedure to increase the feed during idle paths, a suppression of chatter [50], and an automated cutting path distribution [50, 51]. As already explained for turning, also for milling some of the described functions of an AC system have lost their significance. Still, tool wear and breakage recognition and chatter detection remain important topics also during milling and the described sensor solutions are being further developed together with suitable signal-processing strategies.

4.3.8
Intelligent Systems for Cutting Processes

There is no clear definition of an intelligent system. Many authors have used this term to describe an unattended machining process, where the tool cuts the workpiece while the process is monitored and controlled by the aid of suitable sensors (eg, [52]). Also, 'intelligent tools' have been presented (eg, [18]), which consist of a specific sensor as an integral part of the tool design. Furthermore, authors sometimes refer to 'intelligent machining operations', which means a model-based cutting simulation for pre-process cutting parameter optimization, followed by an adaptive controlled machining operation [53]. In the previous sections different sensor solutions and typical measurement results have been explained, where every sensor was treated as isolated. However, in many investigations the authors have chosen a multiple sensor approach to solve the desired task of monitoring the whole cutting process. Just to mention a few possibilities, force measurement was often combined with acceleration measurement or power or acoustic emission monitoring. The individual task of the single sensor is still the same, the major challenge is to combine the different signals in a system to obtain as much information as possible about the current process conditions. This parallel consideration of several sensors signals in a computer-based system with the aim of adjusting the process conditions on-line in case of determined problems might be regarded as an intelligent system in the context of this survey. One of the most important factors to promote this idea is the development of open-architecture control units for CNC machine tools. The different sensors necessary will also have a modular design to allow easy and fast integration in the machine tool control [52]. Owing to the complexity of cutting processes, techniques of artificial intelligence such as neural networks and fuzzy logic are attracting increasing attention and are already in use (eg, [35, 54]). The effort to train these artificial intelligence systems is still very great, but because of the rapid progress in computer hardware and software, further time reductions for some tasks are expected. Still one major problem is to understand clearly and define the role and monitoring task of every chosen sensor. As reported in [54], the parallel signal processing of different sensors in a neural network to estimate drill wear does not necessarily improve the monitoring accuracy. Rather, a deterioration of the correct estimation occurred, because the sensors for power, thrust force, and torque gave only redundant information for the specific task of drill wear detection. This result reveals the definite necessity to choose initially the right sensor, mounting position, and signal processing strategy before an intelligent system for cutting processes can be established. In this context, the previous sections should provide some useful information.

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4.4
Abrasive Processes

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4.4.1
Introduction

Abrasive processes, which are mostly applied for achieving high accuracy and high quality of mechanical, electrical, and optical parts, can be divided into two categories, fixed abrasive processes and loose abrasive processes. In fixed abrasive processes, grinding wheels or honing stones are used as tools and the abrasives are held together with bonding material, also providing sufficient pores for chip removal. In loose abrasive processes, the individual grains are not fixed and are usually supplied together with a carrier medium. Among various types of abrasive processes, grinding is most widely applied in the industry. This is due to the fact that the modern grinding technology can meet the demands of not only high-precision machining but also a high material removal rate. In addition, some difficult to cut materials, such as engineering ceramics, can only be machined with abrasive processes.

4.4.2
Problems in Abrasive Processes and Need for Monitoring

The behavior of any abrasive process is very dependent on the tool performance. The grinding wheel should be properly selected and conditioned to meet the requirements on the parts. In addition, its performance may change significantly during the grinding process, which makes it difficult to predict the process behavior in advance. Conditioning of the grinding wheel is necessary before the grinding process is started. It becomes necessary also after the wheel has finished its life to restore the wheel configuration and the surface topography to the initial state. This peripheral process needs sufficient sensor systems to minimize the auxiliary machining time, to assure the desired topography, and to keep the amount of wasted abrasive material during conditioning to a minimum.

Sensor systems for a grinding process should also be capable of detecting any unexpected malfunctions in the process with high reliability so that the production of sub-standard parts can be minimized. Some major problems in the grinding process are chatter vibration, grinding burning, and surface roughness deterioration. These problems have to be identified in order to maintain the desired workpiece quality.

In addition to problem detection, another important task of the monitoring system is to provide useful information for optimizing the grinding process in terms of the total grinding time or the total grinding cost. Optimization of the process will be achieved if the degradation of the process behavior can be followed with the monitoring system. The information obtained with any sensor system during the grinding process can be also used for establishing databases as part of intelligent systems.

4.4.3
Sensors for Process Quantities

As for all manufacturing processes, it is most desirable to measure the quantities of interest as directly and as close to their origin as possible. Every abrasive process is determined by a large number of input quantities, which may all have an influence on the process quantities and the resulting quantities. Brinksmeier proposed a systematic approach to distinguish between different types of quantities to describe a manufacturing process precisely [1]. The hardware components used such as machine tool, workpiece, tools, type of coolant, etc., are described as system quantities. The settings are further separated into primary and secondary quantities; the former comprise all relevant input variables of the control which describe the movement between tool and workpiece whereas the latter do not have an influence on the relative motion for material removal, such as dressing conditions or coolant flow rate. In addition, disturbing quantities also have to be taken into account, often leading to severe problems concerning the demand for constant high quality of the manufactured product. All these input quantities have an effect on the process itself, hence the mechanical and thermal system transfer behavior is influenced. Owing to the interaction of tool and workpiece, the material removal is initiated and the zone of contact is generated. Only during this interaction process can quantities be detected. The measurement of these by use of adequate sensors is the subject of this section.

The most common sensors to be used in either industrial or research environments are force, power, and acoustic emission (AE) sensors [2]. Figure 4.4-1 shows the set-up for the most popular integration of sensor systems in either surface or outer diameter grinding.

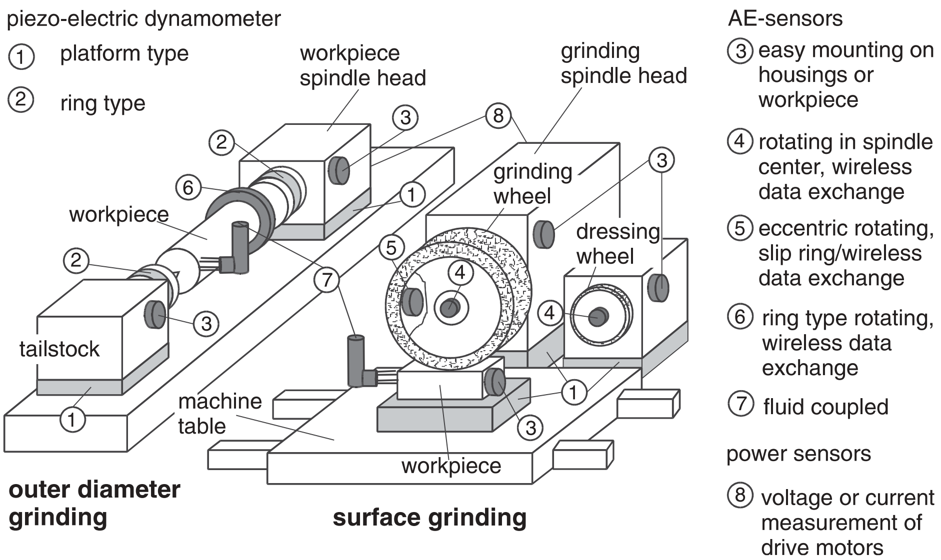
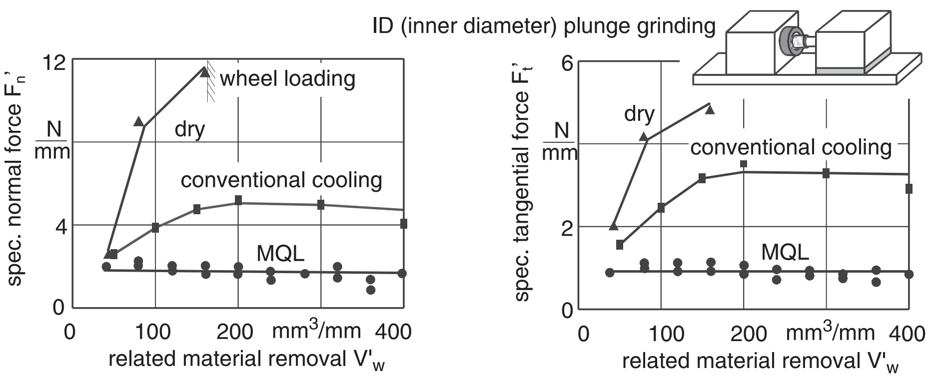


Fig. 4.4-1 Possible positions of force, AE, and power sensors in grinding

4.4.3.1 **Force Sensors**

The first attempts to measure grinding forces go back to the early 1950s and were based on strain gages. Although the system performed well to achieve substantial data on grinding, the most important disadvantage of this approach was the significant reduction in the total stiffness during grinding. Hence research was done to develop alternative systems. With the introduction of piezoelectric quartz force transducers, a satisfactory solution was found. In Figure 4.4-1, different locations for these platforms in grinding are shown. In surface grinding most often the platform is mounted on the machine table to carry the workpiece. In inner (ID) or outer (OD) diameter grinding this solution is not available owing to the rotation of the workpiece. In this case either the whole grinding spindle head is mounted on a platform or the workpiece spindle head and sometimes also the tailstock are put on a platform.

Figure 4.4-2 shows an example of a force measurement with the grinding spindle head on a platform during ID plunge grinding. In this case the results are used to investigate the influence of different coolant supply systems while grinding case hardened steel. The force measurements make it clear that it is not possible to grind without coolant using the chosen grinding wheel owing to wheel loading and high normal and tangential forces. However, it is also seen that there is a high potential for minimum quantity lubrication (MQL) with very constant force levels over the registered related material removal [3]. For OD grinding it is also possible to use ring-type piezoelectric dynamometers. With each ring again all three perpendicular force components can be measured; they are mounted under preload behind the non-rotating center points. To complete possible mounting positions of dynamometers in grinding machines, the dressing forces can also be monitored by the use of piezoelectric dynamometers, eg, the spindle head of rotating dressers can be mounted on a platform. Besides these general solutions, many special set-ups have been used for non-conventional grinding processes



workpiece:
16 MnCr 5, 62 HRC
d_w = 40 mm, v_{ft} = 1 m/s
Q'_w = 1 mm³/mms
grinding wheel:
5SG100LVS (MK-Al_2O_3)

d_s = 30 mm, v_c = 40 m/s
dressing conditions:
diamond cup wheel D301
U_d = 20, q_d = 0,6
a_{ed} = 3 µm, a_{pd} = 1 mm

conventional cooling:
mineral oil, Q = 11 l/min
MQL (minimum quantity lubrication):
ester, Q = 0, 4 ml/min

Fig. 4.4-2 Grinding force measurement with platform dynamometer. Source: Brunner [3] such as ID cut-off grinding of silicon wafers and ID grinding of long small bores with rod-shaped tools.

As already stated for cutting, also for abrasive processes the application of dynamometers can be regarded as state of the art. The problems of high investment and missing overload protection are also valid.

However, wire strain gages are also still in use. For example, the force measurement in a face grinding process of inserts is not possible with a piezoelectric system owing to limited space. In this case an integration of wire strain gages with a telemetric wireless data exchange was successfully applied [4].

4.4.3.2 **Power Measurement**

As explained for cutting in Section 4.3.3.3, the measurement of power consumption of a spindle drive can be regarded as technically simple. Also for abrasive processes the evidence is definitely limited. The amount of power used for the material removal process is always only a fraction of the total power consumption. Nevertheless, power monitoring of the main spindle is widely used in industrial applications by defining specific thresholds to avoid any overload of the whole machine tool due to bearing wear or any errors from operators or automatic handling systems. However, there are also attempts to use the power signal of the main spindle in combination with the power consumption of the workpiece spindle to avoid grinding burn. This approach is further discussed in Section 3.3.

4.4.3.3 **Acceleration Sensors**

In Section 4.3.3 the difficulty of separating acceleration sensors from AE sensors has already been mentioned. In abrasive processes the major application for acceleration sensors is related to balancing systems for grinding wheels. Especially large grinding wheels without a metal core may have significant imbalance at the circumference. With the aid of acceleration sensors the vibrations generated by this imbalance are monitored during the rotation of the grinding wheel at cutting speed. Different systems are in use to compensate this imbalance, eg, hydro compensators using coolant to fill different chambers in the flange or mechanical balancing heads, which move small weights to specific positions. Although these systems are generally activated at the beginning of a shift, they are able to monitor the change of the balance state during grinding and can continuously compensate the imbalance.

4.4.3.4 **Acoustic Emission Systems**

Systems based on AE must be regarded as very attractive for abrasive processes. An introduction to the AE technique and a brief explanation of the physical background is given in Section 3.3.3.4. Figure 4.4-1 shows the possible mounting positions for AE sensors on different components of a grinding machine. Either the spindle drive units, the tool and grinding wheel, or the workpiece can be equipped with a sensor. In addition, fluid-coupled sensors are also in use without any direct mechanical contact to one of the mentioned components. As pointed out before, the time domain course of the root mean square value $U_{\mathrm{AE,\,RMS}}$ is one of the most important quantities for characterizing the process state. In Figure 4.4-3 as an example the correlation between the surface roughness of a ground workpiece and the root mean square value of the AE signal is shown [5].

A three-step OD plunge grinding process with a conventional corundum grinding wheel was monitored. It is obvious that for a dressing overlap of $U_{\mathrm{d}}=2$ the generated coarse grinding wheel topography is leading to a high initial surface roughness of $R_{\mathrm{z}}=5$ µm. Owing to continuous wear of the grains, the roughness even increases during the material removal. For the finer dressing overlap of $U_{\mathrm{d}}=10$ a smaller initial roughness with a significant increase can be seen for the first parts followed by a decreasing tendency. This tendency of the surface roughness is also represented by the AE signal. Higher dressing overlaps lead to more cutting edges, thus resulting in a higher AE activity. The sensitivity of the fine finishing AE signal is higher, because the final roughness is mainly determined in this process step. Meyen [5] has shown in many other tests that monitoring of the grinding process with AE is possible.

In recent years, research has been conducted on high-resolution measurement of single cutting edges in grinding. The root mean square value must be regarded as an average statistical quantity, usually often low-pass filtered and thus not really suitable to reveal short transient effects such as single grit contacts. Webster et al. observed burst-type AE signals of single grits in spark-in and spark-out stages of different grinding operations by analyzing the raw AE signals with a special high-speed massive storage data acquisition system [6].

In addition to these time-domain analyses, the AE signal can also be investigated in the frequency domain. Different effects such as wear or chatter vibration have different influences on the frequency spectrum, so it should be possible to

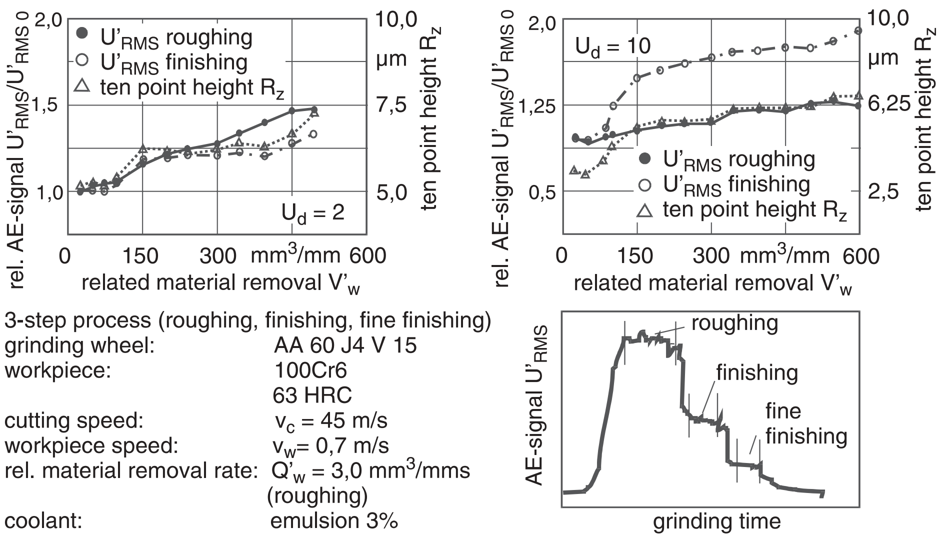


Fig. 4.4-3 Correlation between surface roughness and the AE r.m.s. signal. Source: Meyen [5]

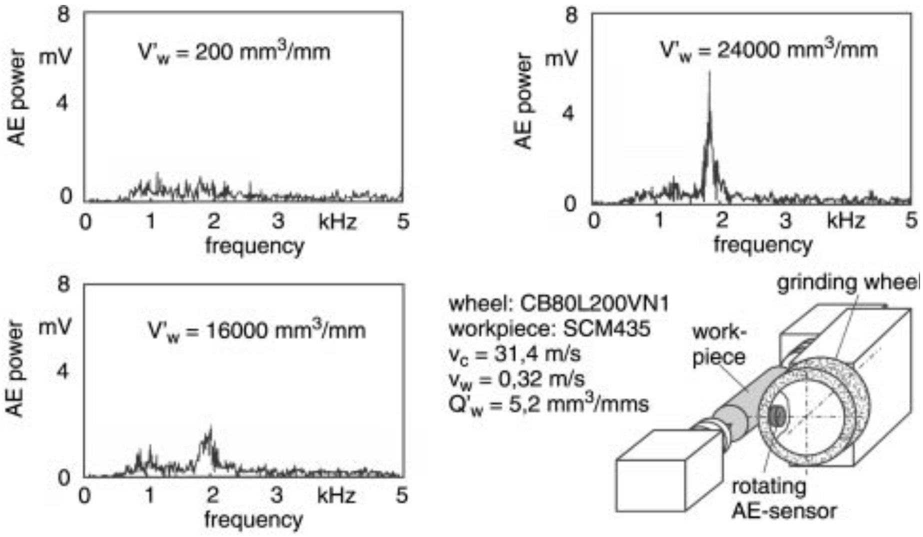


Fig. 4.4-4 Acoustic emission frequency analysis for chatter detection in grinding. Source: Wakuda et al. [7]

use the frequency analysis to separate these effects. Figure 4.4-4 shows the results of a frequency analysis of the AE signal in OD plunge grinding with a vitreous bond CBN grinding wheel [7]. As a special feature the AE-sensor is mounted the grinding wheel core and transfers the signals via a slip ring to the evaluation computer, so both grinding and dressing operations can be monitored. The results reveal that no significant peak can be seen after dressing and first grinding tests. Only after a long grinding time do specific frequency components emerge from the spectrum which show a constantly rising power during the continuation of the test. The detected frequency is identical with the chatter frequency, which could be determined by additional measurements. The AE-signals were used as input data for a neural network to identify automatically the occurrence of any chatter vibrations in grinding [7].

Owing to the general advantages of AE sensors and their variety, almost any process with bond abrasives has already been investigated with the use of AE. Surface grinding, ID and OD grinding, centerless grinding, flexible disk grinding, gear profile grinding, ID cut-off grinding of silicon wafers, honing, and grinding with bond abrasives on tape or film type substrates have all been subjects of AE research.

4.4.3.5 **Temperature Sensors**

In any abrasive process, mechanical, thermal, and even chemical effects are usually superimposed in the zone of contact. Grinding in any variation generates a significant amount of heat, which may cause a deterioration of the dimensional accuracy of the workpiece, an undesirable change in the surface integrity state, or increased wear of the tool. In Section 3.3.3.3 some sensors for temperature measurement have already been explained. Figure 4.4-5 shows the most popular temperature mea-

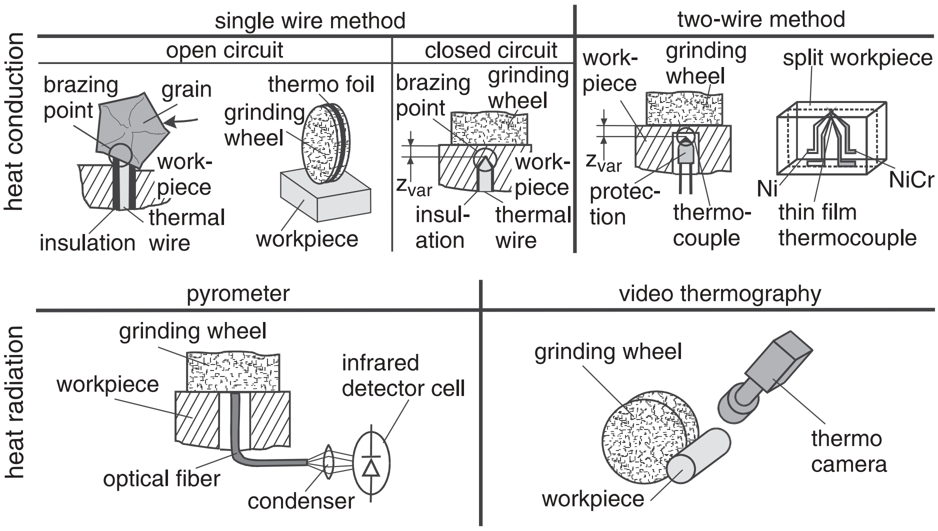


Fig. 4.4-5 Temperature measurement systems in grinding

surement devices. The preferred method for temperature measurement in grinding is the use of thermocouples. The second metal in a thermocouple can be the workpiece material itself; this set-up is called the single-wire method.

A further distinction is made according to the type of insulation. Permanent insulation of the thin wire or foil against the workpiece by use of sheet mica is known as open circuit. The insulation is interrupted by the individual abrasive grains, hence measurements can be repeated or process conditions varied until the wire is worn or damaged. Many workers (eg, [8]) have used this set-up. Also the grinding wheel can be equipped with the thin wire or a thermo foil, if the insulation properties of abrasive and bond material are adequate. In the closed-circuit type, permanent contact of the thermal wire and the workpiece by welding or brazing is achieved. The most important advantage of this method is the possibility of measuring temperatures at different distances from the zone of contact until the thermocouple is finally exposed to the surface. For the single-wire method it is necessary to calibrate the thermocouple for each different workpiece material. This disadvantage is overcome by the use of standardized thermocouples, where the two different materials are assembled in a ready-for-use system with sufficient protection. A large variety of sizes and material combinations are available for a wide range of technical purposes. With this two-wire method it is again possible to measure the temperatures at different distances from the zone of contact. This approach can be regarded as most popular for temperature measurement in grinding. A special variation of this two-wire method is the use of thin-film thermocouples [8, 9], (see also Section 3.3.3.3). The advantage of this method is an extremely small contact point to resolve temperatures in a very small area and the possibility of measuring a temperature profile for every single test depending on the number of evaporated thermocouples in simultaneous use.

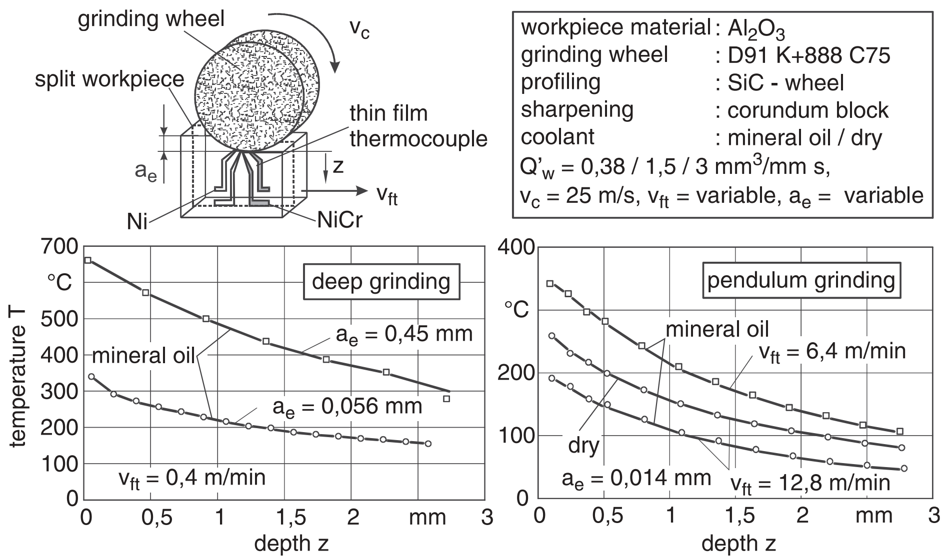


Fig. 4.4-6 Grinding temperature measurement with thin-film thermocouples. Source: Lierse [9]

In Figure 4.4-6, temperature measurements during grinding of Al_2O_3 ceramic with a resin-bonded diamond grinding wheel using these thin-film thermocouples are shown [9]. Obviously the setting quantities have a significant influence on the generation of heat in the zone of contact. Especially the heat penetration time is of major importance. In deep grinding with a very low tangential feed speed, high temperatures are registered, whereas higher tangential feed speeds in pendulum grinding lead to a significant temperature reduction. As expected, the avoidance of coolant leads to higher temperatures compared with the use of mineral oil.

However, in any case for either single- or two-wire methods the major disadvantage is the great effort needed to carry out these measurements. Owing to the necessity to install the thermocouple as close as possible to the zone of contact, it is always a technique where either the grinding wheel or workpiece have to be specially prepared. Hence all these methods are only used in fundamental research; industrial use for monitoring is not possible owing to the partial destruction of major components.

In addition to these heat conduction-based methods, the second group of usable techniques is related to heat radiation. Infrared radiation techniques have been used to investigate the temperature of grinding wheel and chips. By the use of a special infrared radiation pyrometer, with the radiation transmitted through an optical fiber, it is even possible to measure the temperature of working grains of the grinding wheel just after cutting [10]. Also the use of coolant was possible and could be evaluated. In any case, these radiation-based systems need careful calibration, taking into account the properties of the material to be investigated, the optical fiber characteristics, and the sensitivity of the detector cell. However, again, for most of the investigations preparation of the workpiece is necessary, as shown in Figure 4.4-5 (bottom left).

The second heat radiation-based method is thermography. For this type of measurement, the use of coolants is always a severe problem, because the initial radiation generated in the zone of contact is significantly reduced in the mist or direct flow of the coolant until it is detected in the camera. Thus the major application of this technique was limited to dry machining. Brunner was able to use a high-speed video thermography system for OD grinding of steel to investigate the potential of dry or MQL grinding [3].

All the mentioned temperature sensors can also be distinguished with regard to their measurement area. Video thermography is a technique to obtain average information about the conditions in the contact zone. For this reason it might be called macroscopic temperature measurement. Pyrometers can either give average information, but as Ueda and others have shown, single-grain measurements can also be conducted depending on the diameter of the optical fibers. Concerning the use of thermocouples, the situation is more difficult. Standard thermocouples and the closed-circuit single-wire method are used to measure at a specific distance from the zone of contact. Thus the average temperature at this point can be detected; the measurement spot might be extremely small, especially in the case of evaporated thin-film thermocouples. This might be called microscopic temperature measurement, but single-grain contact detection is not possible. The open-circuit method with the thin thermal wire, which is exposed to the surface, is the only real microscopic temperature measurement technique, because in this case single grains generate the signal. However, the response time of this system is significant, so it must be established critically whether all single contacts can be registered.

4.4.4
Sensors for the Grinding Wheel

The grinding wheel state is of substantial importance for the achievable result. The tool condition can be described by the characteristics of the grains. Wear can lead to flattening, breakage, and even pullout of whole grains. Moreover, the number of cutting edges and the ratio of active to passive grains are of importance. Also the bond of the grinding wheel is subject to wear.

Owing to its hardness and composition, it influences significantly the described variations of the grains. In any case, wheel loading generates negative effects due to insufficient chip removal and coolant supply. All these effects can be summarized as grinding wheel topography, which changes during the tool life between two dressing cycles. As a resulting effect, the size of the grinding wheel and its diameter are reduced. In most cases dressing cycles have to be carried out without any information about the actual wheel wear. Commonly, grinding wheels are dressed without reaching their end of tool life in order to prevent workpiece damage, eg, workpiece burn. Figure 4.4-7 gives an overview of different geometric quality features concerning the tool life of grinding wheels. As a rule the different types of wheel wear are divided into macroscopic and microscopic features. Many attempts have been made to describe the surface topography of a grinding wheel and to correlate the quantities

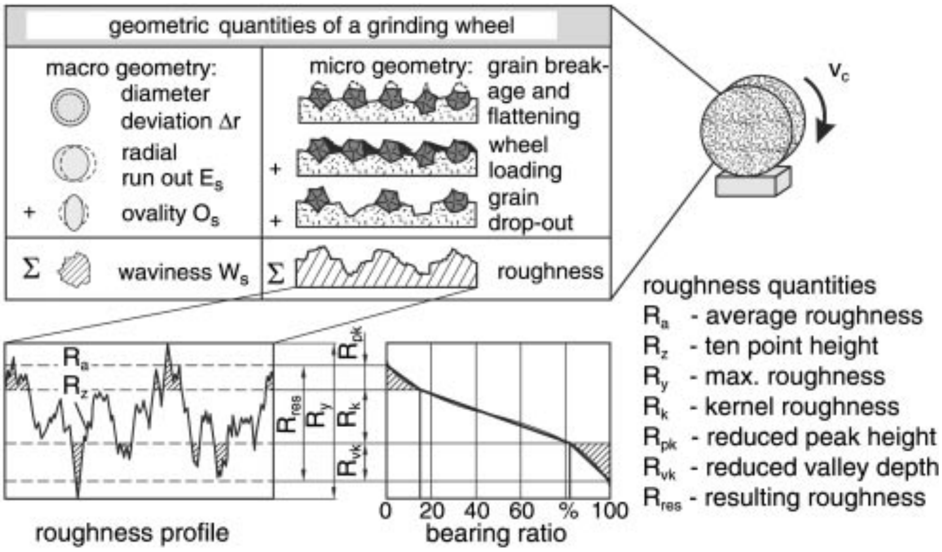


Fig. 4.4-7 Geometric quantities of a grinding wheel

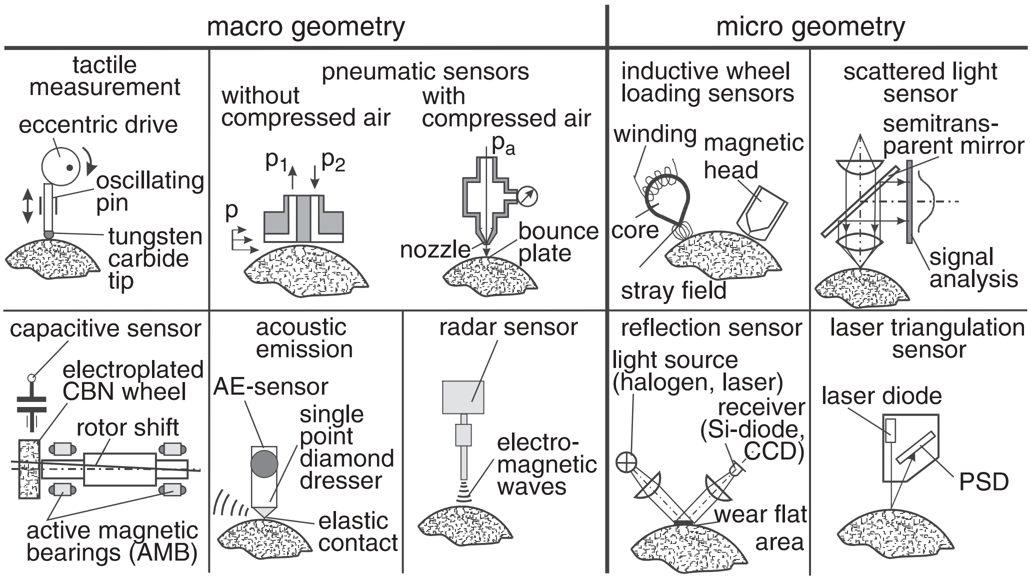


Fig. 4.4-8 Sensors for grinding wheel topography measurement

with the result on the workpiece. All methods that need a stationary object in a laboratory surrounding, which means that the grinding wheel is not rotating and even dismounted, will not be discussed. Attention is focused on dynamic methods, which are capable of being used in the grinding machine during the rotation of the tool. If only the number of active cutting edges is of interest, some already introduced techniques can be used. Either piezoelectric dynamometers or thermocouple methods have been used to determine the number of active cutting edges.

In Figure 4.4-8 other methods are introduced that are suitable for dynamic measurement of the grinding wheel. Most of the systems are not able to detect all micro- and macro-geometric quantities, and can only be used for special purposes.

4.4.4.1 **Sensors for Macro-geometric Quantities**

The majority of sensors are capable of measuring the macro-geometric features. Any kind of mechanical contact of a sensor with the rotating tool causes serious problems, because the abrasives always tend to grind the material of the touching element. Only by realizing short touching pulses with small touching forces and by using a very hard tip material such as tungsten carbide is it possible to achieve satisfactory results. For instance, such a system with an eccentric drive to realize the oscillation of the pin to measure the radial wheel wear at cutting speeds of up to 35 m/s has been used [11]. However, coolant supply and corundum grinding wheels with a porous vitreous bond caused severe problems. In any case, these tactile-based methods on rotating tools are only suitable for macro-geometric measurement and are limited to a few studies.

Another group of sensors for the measurement of grinding wheels is based on pneumatic systems. Although this method is in principle also not able to detect the micro-geometric features of a grinding wheel owing to the nozzle diameter of 1 mm or more, they are important for determining the macro-geometry. Systems with compressed air supply and those without have to be distinguished. The latter are characterized by measurement of the airflow around the rotating grinding wheel. The results obtained reveal a dependence of the airflow on the distance of the sensor from the surface, on the circumferential speed, and to a small extent on the topography of the grinding wheel. The method with a compressed air supply is based on the nozzle-bounce plate principle, with the grinding wheel being the bounce plate. These systems are capable of measuring the distance changes and radial wear with a resolution of 0.2 μm. Especially this feature and the comparatively easy set-up and moderate costs are the main reasons why pneumatic sensors have already found acceptance in industrial application.

Another possibility of registering the macro-geometry of a grinding wheel has been reported [12]. In high-speed ID grinding with CBN wheels, a spindle with active magnetic bearings (AMBs) was used to achieve the necessary circumferential speed of 200 m/s with small-diameter wheels. These spindles have the opportunity to shift the rotor from rotation around the geometric center axis to the main axis of inertia to compensate any imbalance. Especially if electroplated CBN wheels are used without the possibility of dressing, it is necessary to use balancing planes. To measure the runout of these grinding wheels on the abrasive layer at very high circumferential speeds, capacitive sensors have shown the best performance.

The AE signal can also be used to determine the macro-geometry of the grinding wheel. In [13] a system was proposed consisting of a single-point diamond dresser equipped with an AE sensor to detect exactly the position of the grinding wheel surface. Because AE signals can be obtained without contact of the dresser and the wheel due to turbulence, in total three different contact conditions can be distinguished, non-contact, elastic contact, and brittle contact. It is proposed to use the AE level of the elastic contact range to monitor the exact position of the grinding wheel. The only disadvantage is the current limitation to a single-point dresser. To overcome this demerit, an extension to rotating dressing tools is the subject of current research [14].

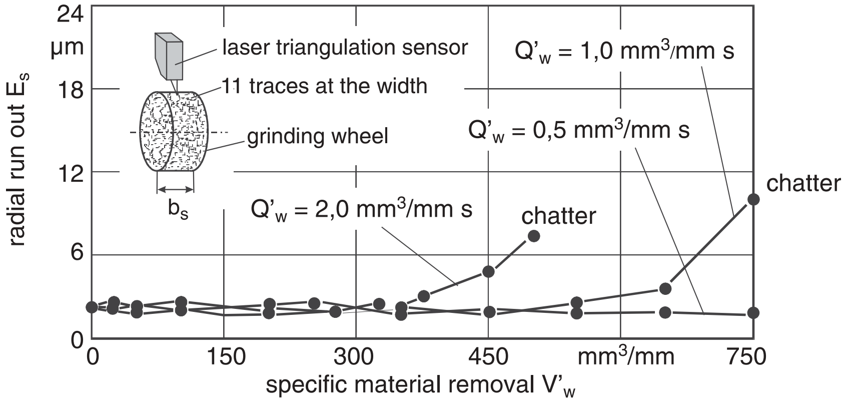
Another principle used to determine radial wheel wear is based on a miniature radar sensor [15]. The usual radar technique is known from speed and traffic control applications with a maximum accuracy in the centimeter range. The sensor used for grinding works on an interferometric principle. With an emitting frequency of 94 GHz and a wavelength of $\lambda=3.18$ mm, this sensor has a measuring range of 1 mm and a resolution of 1 µm. The main advantages are the robustness against any dust, mist, or coolant particles and the possibility of measuring on any solid surface. The sensor has been used in surface grinding of turbine blades with continuous dressing (CD). A control loop was established to detect and control the radial wear of the grinding wheel taking into account the infeed of the dressing wheel.

4.4.4.2 **Sensors for Micro-geometric Quantities**

In addition to these systems for macro-geometric features, other sensors are able to give information about the micro-geometry. The loading of a grinding wheel with conductive metallic particles as a special type of micro-geometric wear can be detected by using sensors based on inductive phenomena. The sensor consists of a high permeability core and a winding. It is positioned at a short distance from the surface. The metallic particles generate a change in the impedance, which can be further processed to determine the state of wheel loading. A conventional magnetic tape recorder head may also be used to detect the presence and relative size of ferrous particles in the surface layer of a grinding wheel. As only this special type of wear in grinding of metallic materials can be detected, these sensors have not achieved practical application.

The mentioned limitations of all the so-far introduced techniques turn the attention towards optical methods. These seem to be very promising because of their frequency range and independence of the surface material. A scattered light sensor was used to determine the reflected light from the grinding wheel surface by using charge-coupled device (CCD) arrays. The first attempts at an optical-based measurement of the topography at cutting speeds were reported in [16]. An opto-electronic sensor with a fast Si photodiode as receiver and either a xenon vapor lamp or halogen light source was used to measure the pulses of reflected light on so-called wear flat areas. Tests have shown that the number of pulses changes during grinding, hence a possible monitoring of the wear state was proposed. However, hardware limitations, especially problems with the light sources, did not lead to further success at that time. Gotou and Touge took up the same principle again [17], keeping the Si photodiode as receiver but this time using a laser source with 670 nm wavelength and a personal computer for control. Grinding wheels in wet-type grinding at 30 m/s could be measured. Again, it was stated that the wear flat areas are registered by the output signal and that these areas change during grinding.

The optical method with the highest technical level so far is based on laser triangulation. The measurement principle and results of micro-geometric characterization of the grinding wheel surface to determine surface integrity changes are



grinding conditions:
grinding wheel: EKW 80K5 V62
q = 60
v_c = 30 m/s = v_{mea}
spark out time: 10 s
multi point diamond dresser
workpiece: 100 Cr 6
ball bearing steel

Fig. 4.4-9 Optical macro-geometric grinding wheel topography measurement

given in Section 3.3.4. In the following, results of macro-geometric measurements will be presented.

As mentioned, no practical limitations exist for the determination of macro-geometric quantities such as radial runout, and the maximum surface speed may even exceed 300 m/s [18]. Figure 4.4-9 shows the result of an investigation of OD plunge grinding of ball-bearing steel with a corundum grinding wheel. Using three different material removal rates, the change of the radial runout as a function of the material removal at 30 m/s was plotted. For the smallest material removal rate no change is detectable from the initial value after dressing. However, for increasing material removal rates of Q'_w=1.0 and 2.0 mm³/mm s the radial runout rises after a specific material removal. In the latter cases the increasing radial runout leads to chatter vibrations with visible marks on the workpiece surface. Obviously the system is capable of detecting significant macro-geometric changes due to wear of the grinding wheel. The limitations of the system regarding the micro-geometric characterization have been discussed in Section 3.3.4.

The examples presented of grinding wheel sensors reveal that the majority of systems are related to macro-geometric features. However, many attempts have been made to establish especially optical systems for the measurement of micro-geometric quantities. The overall limitation for these techniques will always be the rough conditions in the working space of a grinding machine with coolant and process residues in the direct contact with the object to be measured. In many cases it is therefore preferable to measure directly the manufactured workpiece itself.

4.4.5 Workpiece Sensors

Two essential quality aspects determine the result of an abrasive process on the workpiece. On the one hand the geometric quality demands have to be fulfilled. These are dimension, shape, and waviness as essential macro-geometric quantities. The roughness condition is the main micro-geometric quantity. However, increasing attention is also paid to the surface integrity state of a ground workpiece owing to its significant influence on the functional behavior. The physical properties are characterized by the change in hardness and residual stresses on the surface and in sub-surface layers, by changes in the structure, and the likely occurrence of cracks (see Section 3.3). All geometric quantities can be determined by using laboratory reference measuring devices. For macro-geometric properties any kind of contact system can be used, eg, 3D coordinate measuring machines, contour stylus instruments, or gages. Roughness measurement is usually performed with stylus instruments giving standardized values, but optical systems are also applied in some cases. Methods to determine physical quality characteristics are mentioned in Section 3.3.

4.4.5.1 Contact-based Workpiece Sensors for Macro-geometry

The determination of macro-geometric properties of workpieces during manufacture is the most common application of sensors in abrasive processes, especially grinding. For decades contact sensors have been in use to determine the dimensional changes of workpieces during manufacturing. A wide variety of in-process gages for all kinds of operation are available. In ID or OD grinding the measuring systems can either be comparator or absolute measuring heads, with the capability of automatic adjustment to different part diameters. The contact tips are usually made of tungsten carbide, combining the advantages of wear resistance, moderate costs, and adequate frictional behavior. The repeatability is in the region of 0.1 μm [19]. Internal diameters can be gaged starting from 3 mm. If constant access to the dimension of interest during grinding is possible, these gages are often used as signal sources for adaptive control (AC) systems (see also Section 4.4-8). The conventional technique for measuring round parts rotating around their rotational axis can be regarded state of the art. The majority of automatically operating grinding machines are equipped with these systems. In the survey of contact sensors for workpiece macro-geometry in Figure 4.4-10 (top left), a more complex measurement set-up is shown. Owing to the development of new drives and control systems for grinding machines, continuous path-controlled grinding of crankshafts has now become possible [20]. The crankshaft is clamped only once in the main axis of the journals. For machining the pins the grinding wheel moves back and forth during rotation of the crankshaft around the main axis to generate a cylindrical surface on the pin. An in-process measurement device for the pin diameter has to follow this movement. A first prototype system was installed in a crankshaft grinding machine. The gage is mounted on the grinding wheel head and

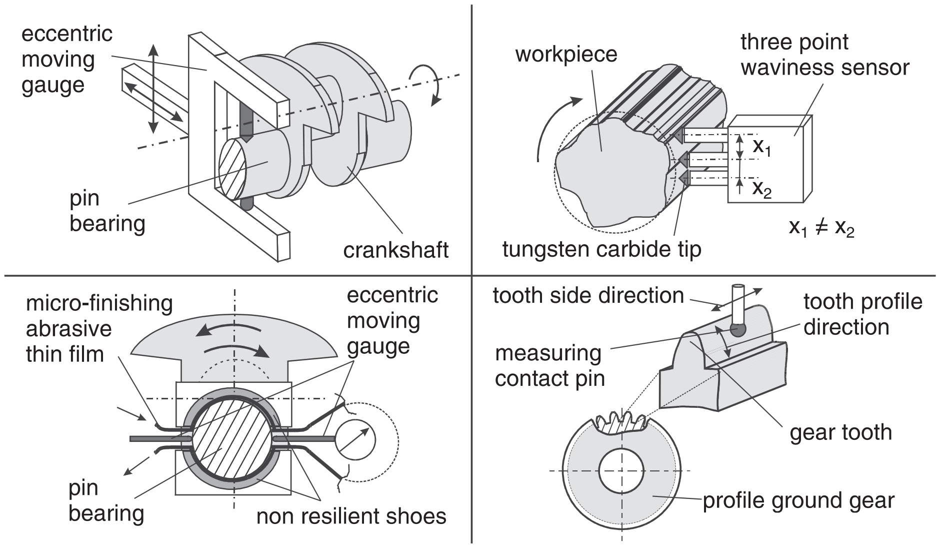


Fig. 4.4-10 Contact sensor systems for workpiece macro-geometry

moves back and forth together with the grinding wheel. A swivel joint effects the height balancing. The same problem of measurement during eccentric movement of a crankshaft pin occurs in the micro-finishing process (Figure 4.4-10, bottom left). This last process in the production chain using single-layer abrasives bond to a thin plastic belt is applied to give the pins and journals the desired final micro-geometry concerning roughness, bearing ratio, and crowning. The abrasive film is automatically indexed before each cycle and pressed by hard, non-resilient, and exactly formed shoes to the workpiece surface at specific controlled pressure. The crankshaft rotates and oscillates for a specific cycle and drags single arms with shoes, belt supply, and measuring gage for each pin and journal at the same time. Size control is realized by a moving gage with contacting pins, which allow stopping of the micro-finishing process on each bearing individually, when the final dimension is reached. A machine tool with this in-process moving size control sensor system is already available.

The detection of waviness on the circumference of rotating symmetrical parts during grinding is more complex owing to the demand for a significantly higher scanning frequency. Foth has developed a system with three contacting pins at non-constant distances to detect the development of waviness on workpieces during grinding as a result of, eg, regenerative chatter [19] (Figure 4.4-10, top right). Only by using this set-up was it possible to identify the real workpiece shape, taking into account the vibration of the workpiece center during rotation. The signal of the waviness sensor was fed back to the control unit of the machine tool. If increasing waviness was determined during grinding, the speed ratio between the rotating grinding wheel and workpiece was changed to suppress regenerative effects. Although the system performance was satisfactory and could meet all industrial demands concerning robustness, it was only used to confirm theoretical simulations. The knowledge gained can be directly applied to grinding machine controls to avoid regenerative chatter, hence waviness sensors are not really needed.

The last example of contact-based macro-geometric measurement in a machine tool is related to gear grinding (Figure 4.4-10, bottom right). Especially for manufacturing of small bath sizes or single components of high value, it is essential to fulfil the 'first part good part' philosophy. For these reasons several gear grinding machine tool builders have decided to integrate an intelligent measuring head in their machines to be able to measure the characteristic quantities of a gear, eg, flank modification, pitch, or root fillet. Usually a measurement is done after rough grinding, before the grinding wheel is changed or redressed for the finish operation. Sometimes also the initial state before grinding is checked to compensate for large deviations resulting from distortions due to heat treatment. Of course, the measurement can only be done if the manufacturing process is interrupted. However, the main advantage is still a significant saving of time. Any removal of the part from the grinding machine tool for checking on an additional gear measuring machine will take a longer time. Also the problem of precision losses due to rechucking is not valid, because the workpiece is rough machined, measured, and finished in the same set-up. These arguments are generally true for any kind of high-value parts with small bath sizes and complex grinding operations. Hence it is not surprising that also in the field of aircraft engine manufacturing new radial grinding machines are equipped with the same kind of touch probe system in the working space. Geometric quality data are acquired on the machine tool before the next grinding operation in the same chuck position is started [21]. Nevertheless, the use of a measuring head in a complex gear or turbine blade grinding machine is not a pure sensor application. The measurement is only possible in auxiliary process time, but between succeeding process steps. It must be stated as a borderline case, but should be included because of the high technical level and industrial relevance.

4.4.5.2 **Contact-based Workpiece Sensors for Micro-geometry**

The determination of micro-geometric quantities on a moving workpiece by using contact sensor systems is a challenging task. Permanent contact of any stylus with the surface is not possible, because the dynamic demands are much too high. Only intermittent contacts can be used to generate a signal, which should be proportional to the roughness. Saljé has introduced a sensor based on a damped mass spring element [22]. The surface of the fast-moving workpiece stimulates self-oscillations of the sensing element, which are correlated with the roughness.

The system was improved and modified in the following years, and a set-up with parallel springs was successfully applied to the honing process [23], (Figure 4.4-11). The sensor was integrated in the honing tool and the pre-amplified signal was transmitted to the evaluation unit via slip ring contact. Figure 4.4-11 shows the result of the calibration of this sensor system with conventional stylus roughness measurements. A linear correlation in the range of interest of R_z = 2–20 μm was found.

Rotating roughness sensors for OD grinding have also been tested, but different limitations concerning diameter and width of the workpiece did not allow

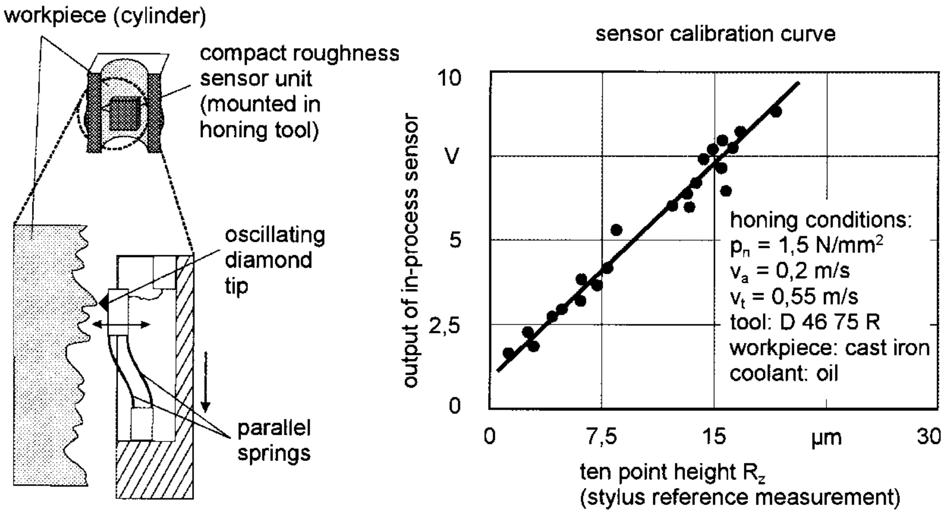


Fig. 4.4-11 Contact workpiece roughness sensor for ID honing. Source: von See [22]

practical application. A second important problem is related to the measuring direction of these in-process sensors. Whether the sensor was combined with the tool in the case of honing or fed towards the workpiece by auxiliary systems, the measuring direction was always in the direction of the abrasive process. Any stylus-type reference measurement is usually done perpendicular to the grinding or honing direction. In the parallel direction the diamond tip is likely to stay in just one groove and then suddenly jump out to the next one. Hence a parallel measurement does not give substantial information on the roughness state and is usually avoided. Although attempts have been made with additional axial feed of the sensor to generate a scroll-type movement on the surface [22], the idea of contacting the surface for roughness measurement did not lead to industrial success.

4.4.5.3 **Contact-based Workpiece Sensors for Surface Integrity**

The range of contact sensors on workpieces is completed with systems related to surface integrity measurement. A description of the available techniques is given in Section 3.3.5.

4.4.5.4 **Non-contact-based Workpiece Sensors**

All the mentioned restrictions of contact sensor systems on the workpiece surface gave a significant push to develop non-contact sensors. As for grinding wheels, again optical systems seem to have a high potential. In Figure 4.4-12 different optical systems and two other non-contacting sensor principles are introduced.

As a very fast optical system for measuring macro-geometric quantities, a laser-scanner is shown. The scanner transmitter contains primarily the beam-emitting He-Ne laser, a rotating polygonal mirror and a collimating lens for paralleling the diffused laser beam. The set-up of the scanner receiver contains a collective lens and a photodiode. The electronic evaluation unit counts the time when the photo-

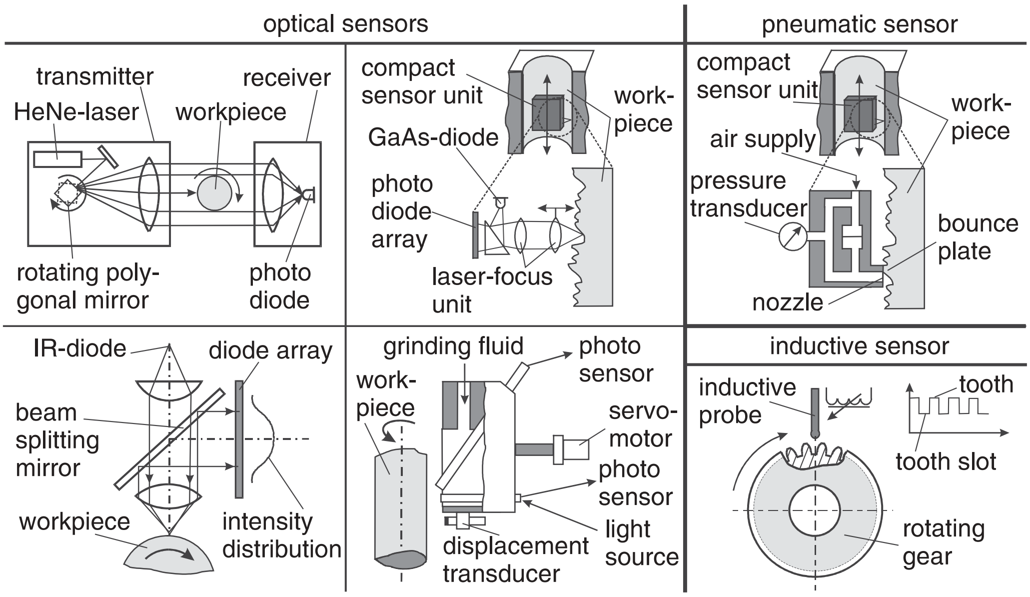


Fig. 4.4-12 Non-contact sensor systems for workpiece quality characterization

diode is covered by the shadow of the object. The diameter is a function of the speed of the polygonal mirror and the time during which the laser beam does not reach the covered photodiode. Conicity can be evaluated by an axial shifting of the workpiece. In principle this optical measurement cannot be performed during the application of coolant. During grinding the system can be protected by air barriers and mechanical shutters. Laser-scanners were first installed in grinding machines to measure the thermal displacement of machine tool components or to determine the profile accuracy of the dressed grinding wheel. For a detailed workpiece characterization, a set-up with a laser-scanner outside of the working space of the grinding machine was preferred. In [24] the layout and realization of a flexible measurement cell incorporating a laser-scanner for the determination of macro-geometric properties was introduced. The system is able to measure automatically the desired quantities within the grinding time, and the information can be fed back to the grinding machine control unit.

For the determination of macro- and micro-geometric quantities a different optical system has to be applied. The basis of a scattered light sensor for the measurement of both roughness and waviness is the angular deflection of nearly normal incident rays. The set-up of a scattered light sensor is shown in Figure 4.4-12 (bottom left). A beam-splitting mirror guides the reflected light to an array of diodes. This array is able to record the distribution only in one optical flat. The alignment of the sensor is therefore of essential importance. To obtain information about the circumferential waviness and roughness, the array has to be perpendicular to the rotation axis of the workpiece. The transverse roughness according to the stylus testing is measurable with a 90° rotation of the sensor. A commercially available system was introduced in the 1980s [25] and used in a wide range of tests. The optical roughness measurement quantity of this system is

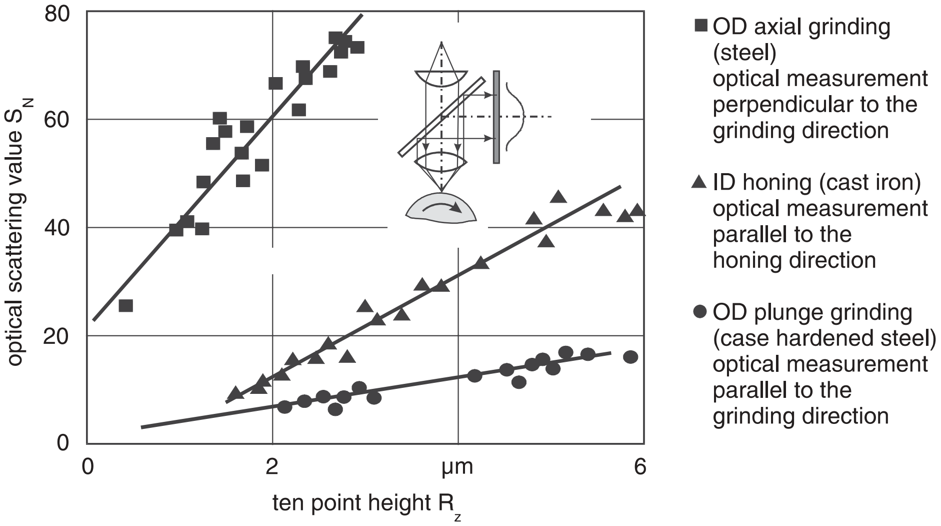


Fig. 4.4-13 Different correlation curves for an optical scattered light sensor. Source: König und Klumpen [27], von See [23], present authors

called the scattering value, S_N, and is deduced from the intensity distribution. In different tests the scattered light sensor was directly mounted in the working space of the grinding machine to measure the workpiece roughness [26]. A compressed air barrier protected the optical system. In all investigations it was tried to establish a correlation between optical and stylus roughness measurements. It is possible to obtain such a close relationship while grinding or honing with constant process parameters [23, 26, 27] (Figure 4.4-13). This restriction is indispensable, because a change of input variables such as dressing conditions or tool specification may lead to workpieces with the same stylus roughness values R_a or R_z but different optical scattering values S_N. If a quantitative roughness characterization referring to stylus values is demanded, a time-consuming calibration will be always necessary. As shown in Figure 4.4-13, the measuring direction also has to be clearly defined to achieve the desired correlation. A second limitation is seen in the sensitivity of the system. The scattered light sensor is able to determine differences in high-quality surfaces, but for roughness states of ten-point height $R_z > 5.0$ µm the scattering value S_N reaches its saturation with decreasing accuracy already starting at $R_z = 3.0$ µm [23]. Hence some relevant grinding or honing operations cannot be supervised by this sensor system.

In addition to the installation in the grinding machine, such a scattered light sensor was also integrated in the mentioned flexible measurement cell [24]. This set-up of optical systems outside the grinding machine but integrated in the close-to-machine control loop seems to be superior to the tests under coolant supply in the grinding machine. After all the mentioned investigations, no industrial application of a scattered light sensor in the working space of a grinding machine tool has been reported.

A different optical sensor is based on a laser diode [28] (Figure 4.4-12, top middle). The sensor is equipped with a gallium arsenide diode, which is commonly used in a CD player. With a lens system the beam is focused on the surface and

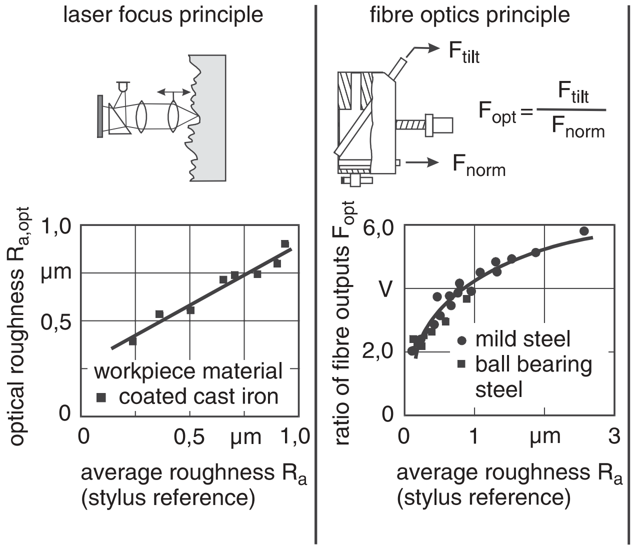


Fig. 4.4-14 Correlation curves for different workpiece roughness sensors. Source: Westkämper [28], present authors

the reflected light is registered on an array of four photodiodes. This system can be used as an autofocus system, with the signal from the four diodes, the focus lens is moved until the best position for minimum diameter is reached. The correlation of the obtained optical average roughness $R_{a,\mathrm{opt}}$ with the stylus reference measurement is shown in Figure 4.4-14 (left). An almost linear dependence of the two different roughness quantities could be found. However, the system is much too slow to be used for any in-process measurement. By using the focus-error signal of the four diodes without moving the lens, it is possible to increase the measurement speed significantly. Another optical approach for in-process roughness measurement is based on the use of optical fiber sensors [29]. The workpiece surface is illuminated through fiber optics and the intensity of the reflected light is detected and evaluated (Figure 4.4-12, middle bottom).

The latter set-up was chosen to increase the sensitivity of the sensor system. The photo-sensor in the normal direction will register less intensity, whereas the inclined photo-sensor will detect more intensity with larger light scattering due to increased roughness. The ratio of the two photo-sensors is related to roughness changes (Figure 4.4-14, middle). A second advantage of the set-up with two fiber optics despite the increased sensitivity is the achieved independence of the workpiece material. Coolant flows around the whole sensor head to make measurement possible during grinding. It is essential to keep the coolant as clean as possible during operation, because the reflection conditions are definitely influenced by the filtering state of the fluid. This is the major drawback of the sensor system, because the coolant quality is not likely to be stable in production. In addition to these mentioned systems, some other optical techniques for on-line measurement of surface topography have been proposed, eg, speckle patterns. Although the measurement speed may allow the installation of these systems in a production line operation, their use as sensors in the machine tool working space is not realistic.

In summary, owing to all the problems related to coolant supply, it must be stated that these conditions do not allow the use of optical systems during grinding or honing as reliable and robust industrial sensors. Only optical sensor applications measuring with interruptions of coolant supply either in the working space of the machine tool or in the direct surrounding have gained importance in industrial production.

In addition to optical sensors, two other principles are also used for non-contact workpiece characterization. A pneumatic sensor as shown in Figure 4.4-12 (top right) was designed and used for the measurement of honed cylinders [30]. The measurement is based on the already mentioned nozzle-bounce plate principle. A correlation with stylus measurements is possible (Figure 4.4-14, right). The main advantages of this system are the small size, the robustness against impurities and coolant, and the fact that an area and not a trace is evaluated. Hence in principle no movement of the sensor during measurement is necessary.

The last system to be introduced as a non-contact workpiece sensor is based on an inductive sensor. The sensor is used in gear grinding machines to identify the exact position of tooth and tooth slot at the circumference of the pre-machined and usually heat-treated gear (Figure 4.4-12, bottom right). The gear rotates at high speed and the signal obtained is evaluated in the control unit of the grinding machine. This signal is used to index the gear in relation to the grinding wheel to define the precise position to start grinding and to avoid any damage to a single tooth. It is also possible to detect errors in tooth spacing. Gears with unacceptable distortions after heat treatment can be identified and rejected to avoid overload of the grinding wheel, especially when using CBN as abrasive.

4.4.6 Sensors for Peripheral Systems

Primary motion between the tool and workpiece characterizes the grinding process, but as already stated at the beginning of Section 4.4 also supporting processes and systems are of major importance. In this section basically the monitoring of the conditioning process and the coolant supply will be discussed.

4.4.6.1 Sensors for Monitoring of the Conditioning Process

The condition of the tool i.e. the grinding wheel is a very decisive factor for the achievable result during the process. Hence the grinding wheel has to be prepared for the desired purpose by using a suitable conditioning technology. The major problem in any conditioning operation is the possible difference between nominal and real conditioning infeed. There are four main reasons for these deviations. The unknown radial grinding wheel wear after removal of a specific workpiece material volume must be regarded as a significant factor. Also the changing relative position of grinding wheel and conditioning tool due to thermal expansion of machine components is relevant. As a third reason, infeed errors related to friction of the guide-ways or control accuracy have to be considered, although their influence is declining in modern grinding machines. The last reason to mention is the wear of the conditioning tool, which of course depends on the individual type. Especially for rotating dressers only after regular use for several weeks can the first wear effects be registered.

Owing to the great importance of the grinding wheel topography, the monitoring of the conditioning operation has been the subject for research for decades. Already in the early 1980s it was first tried to use an AE-based system for the monitoring of the dressing operation [31]. At that time the work was concentrated on the dressing of conventional grinding wheels with a static single-point diamond dresser. The AE sensor was mounted on the dresser and connected to an evaluation unit. It was possible to detect first contact of the dresser and the grinding wheel and the AE intensity could be used to determine the real dressing infeed as a function of dressing feed rate and grinding wheel speed. The dressing feed speed could also be identified by the AE signal [32]. In addition, it was stated that the AE signal reacts significantly faster to the first contact of dressing tool and grinding wheel compared with the monitoring of the spindle power. Further improvements also allowed information to be obtained about the actual profile of the single-point diamond dresser. The limitation to straight cylindrical profiles was overcome by Meyen, who developed a system capable of detecting dressing errors on any complex grinding wheel profile [5] (Figure 4.4-15).

The strategy comprises the determination of a sliding average value with static and dynamic thresholds for every single dressing stroke. The different geometry elements are identified and the currently measured AE signal is compared with the reference curve, which has to be defined in advance. With the calculation of further statistical quantities such as standard deviation or mean signal inclination, it is possible to identify the typical dressing errors in the case of the thresholds being exceeded.

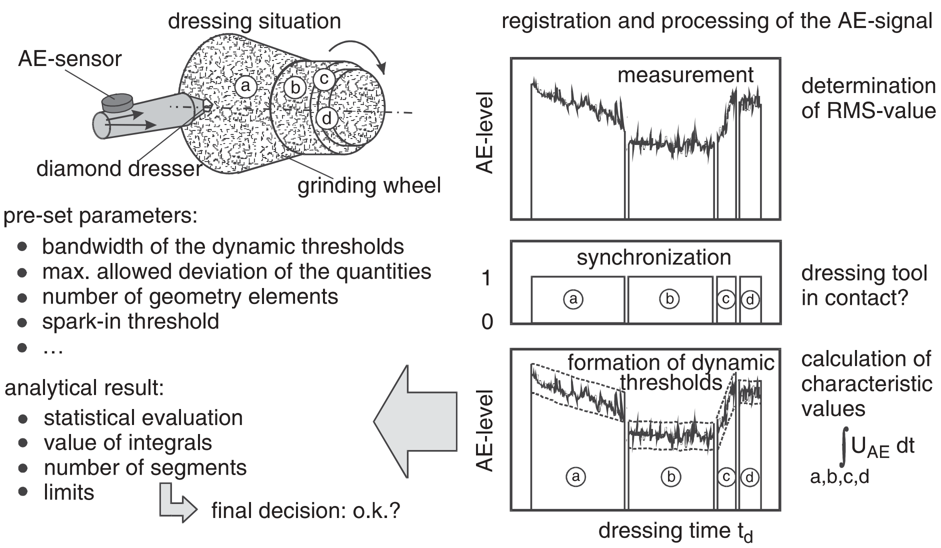


Fig. 4.4-15 Dressing diagnosis for random grinding wheel profiles with AE signals. Source: Meyen [5]

As a consequent next step, AE systems were tested for conditioning operations of superabrasives such as CBN (eg, [7, 33]). The high hardness and wear resistance of these grinding wheels require a different conditioning strategy and monitoring accuracy compared with conventional abrasives. The conditioning intervals due to the superior wear resistance can amount to several hours. The dressing infeed should be limited to a range between 0.5 and 5 μm instead between 20 and 100 μm for conventional wheels in order to save wheel costs. Especially for vitreous bonded CBN grinding wheels it was proposed to use very small dressing infeeds more frequently in order to avoid additional sharpening. This strategy, known as 'touch dressing', revealed the strong demand to establish a reliable contact detection and monitoring system for dressing of superabrasives. In most cases rotating dressing tools are used. The schematic set-up of a conditioning system with a rotary cup wheel, which is often used on internal grinding machines, is shown in Figure 4.4-16.

The conditioning cycle consists of four stages: fast approach, contact detection, defined infeed, and new initiation. The setting parameters such as number of strokes, dressing infeed, and dressing feed rate are stored in the control unit of the grinding machine. The fast approach is done with the NC axis of the machine. The dressing tool is moved to the last-stored dressing position with an additional safety distance of, eg, 20 μm to avoid any undesired contact. Then the dressing sub-program is started with the chosen infeed and feed rate of the dressing tool for each stroke. In this state, a reference signal for the chosen contact detection system can be recorded. In addition to AE techniques, other methods have also been tested. Heuer additionally investigated the possibility of using either the required power of the dressing tool spindle or a piezoelectric force measurement for monitoring [33]. The latter technique was possible, because a piezoelectric actuator was installed as a high-precision positioning system for the infeed of the dressing tool. With this additional equipment infeed extents of 0.25 μm could be

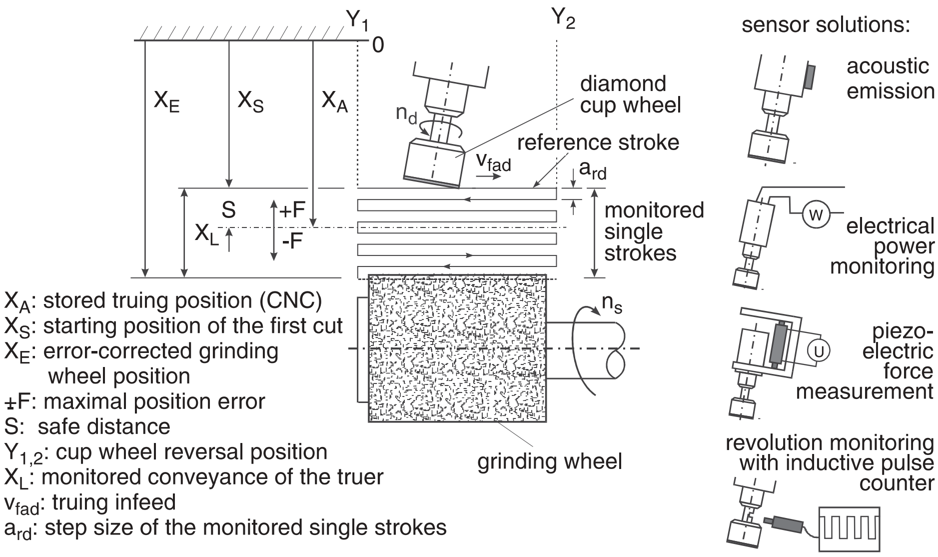


Fig. 4.4-16 Dressing monitoring with rotating diamond tools. Source: Heuer [33]

realized. Hence this system may also upgrade older machine tools with less accuracy. However, in any modern machine tool the in-built x-axis provides the infeed. A further technique for contact detection was introduced in [34]. The measurement of the rotational speed change of the high-frequency dressing spindle, which gives a maximum number of revolutions of 60 000 min^{-1}, was used to determine not only the first contact, but also the whole dressing process. After contact detection of any of the mentioned systems, the conditioning program is continued until the desired number of strokes and infeed are reached. Depending on the type of system it is possible to monitor the course of the signal on the whole width of the grinding wheel. Thus uneven macro-geometric wear of the wheel can be registered, if the measured signal does not exceed the defined threshold reference level over the whole width. This strategy also assures a perfect macro-geometric shape after conditioning. After finishing the conditioning process the final position of the machine x-axis is stored to initialize the next operation.

The use of AE sensors for contact detection of the conditioning and dressing operation can be regarded as state of the art. Many different systems are available. New grinding machine tools with self-rotating conditioning tools are usually equipped with an AE system already in the delivery state. Also the system with dressing spindle rotational speed monitoring has found acceptance in industry, because this system is regarded as very robust and is not influenced by coolant supply or bearing noise, which is still regarded as the major limitation for all AE systems. However, the importance of this last method is declining, because in modern machine tools the control loops for the main drives are extremely fast and thus a deviation in rotational speed is no longer a suitable signal source. Hence the monitoring of the electrical power consumption of the dressing spindle is becoming more attractive, because it has also reached sufficient sensitivity and is installable with the least effort.

4.4.6.2 **Sensors for Coolant Supply Monitoring**

Relatively large contact areas characterize abrasive processes and especially grinding operations. The large number of cutting edges generates a considerable amount of heat in the zone of contact. Hence the reduction of friction and cooling of the interacting parts is often necessary to avoid thermal damage. Therefore, in almost all cases coolants are used to reduce heat and to provide sufficient lubrication. These are the main functions of any coolant supply. Furthermore, the removal of chips and process residues from the workspace of the machine tool, the protection of surfaces, and human compatibility should be provided. Modern coolant compositions also try to fulfil the contradictory demands of long-term stability and biological recyclability.

At least with the wider use of superabrasives such as CBN, the possibility of high-speed grinding, and highly efficient deep grinding, a closer view on the coolant supply began. Coolant pressure and flow rate measured with a simple flowmeter in the coolant supply tube before the nozzle are now often part of the parameter descriptions. Different authors have also worked on the influence of different nozzle de-

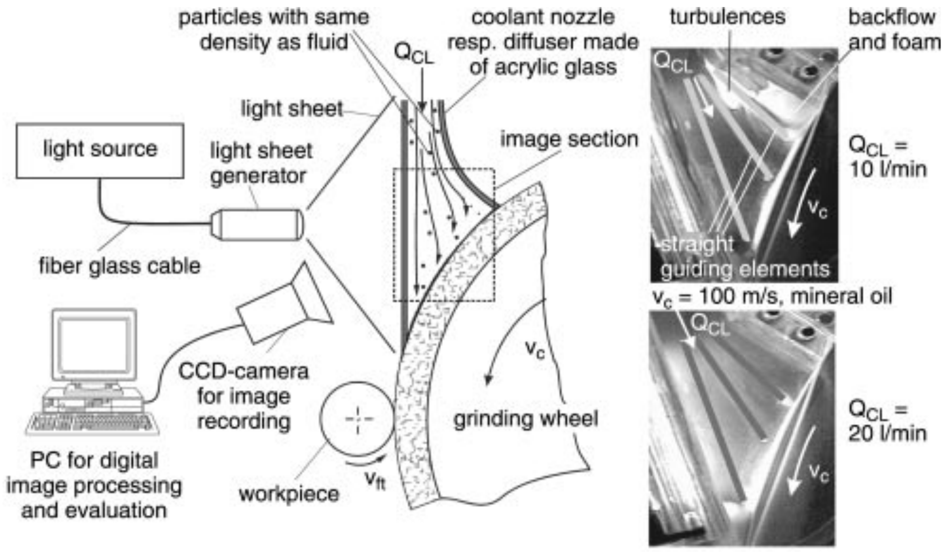


Fig. 4.4-17 Flow behavior monitoring by means of particle image velocimetry. Source: Brinksmeier et al. [37]

signs (eg, [33]). In most cases the influence of different supply options such as conventional flooding nozzles, shoe, spot jet, or spray nozzles, or even internal supply through the grinding wheel, is described by using the already-mentioned process quantities such as forces or temperature [35]. However, in addition to the technological demands, environmental aspects of manufacturing have also attracted significantly more attention. Especially the last mentioned point has led to a detailed investigation of coolant supply and the possibility of reducing or avoiding coolants in grinding completely [36]. Heinzel and co-workers made a very systematic approach to investigate the coolant-related influences and to optimize the relevant parameters and designs. For the development of a suitable shoe nozzle design a special flow visualization technique was used (Figure 4.4-17) [35, 37].

Tracer particles with almost the same density are added to the transparent fluid. All parts of the nozzle of interest are made from acrylic glass and a CCD camera records the flow images perpendicular to the light sheet plane. Although only a qualitative result is available, this technique offers the possibility of systematically studying and improving the whole design of coolant nozzles. As an example, in Figure 4.4-17 (right) the flow behavior of a nozzle with straight guiding elements at two different flow rates is shown. The coolant is mineral oil and the grinding wheel is rotating at a speed of 100 m/s. For the lower flow rate of 10 L/min inhomogeneous flow behavior can be observed. Turbulences, backflow, and foam between top and center guiding elements and at the entry side of the grinding wheel are visible. A doubling of the flow rate leads to steady flow behavior. In [35] it is explained in detail that different flow rates need different adapted guiding elements to achieve the best result.

In addition to this use of an optical monitoring method to optimize the design of coolant nozzles, a special sensor installation for pressure and force investigations was also introduced [35]. The force measurement is done by an already-discussed

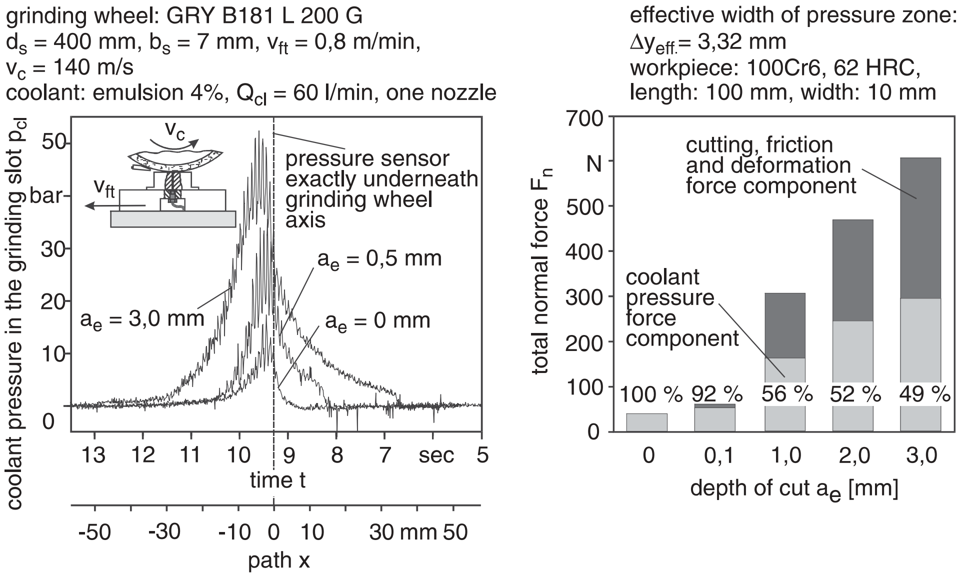


Fig. 4.4-18 Coolant supply monitoring with pressure sensor and dynamometer. Source: Heinzel [35]

piezoelectric dynamometer. During grinding only the total normal force can be registered by this instrument. The idea is to separate the normal force component used for cutting, friction, and deformation from the component that results from the build-up of the hydrostatic pressure between grinding wheel and workpiece and because of the impact of the coolant flow on the surfaces. For this purpose an additional pressure sensor is integrated in the workpiece carrier, allowing the measurement of the pressure course over a grinding path through a bore in the workpiece.

In Figure 4.4-18, results of this sensor configuration are shown [35]. The left part shows a result of the pressure measurement depending on different depths of cut. It is shown that with increasing infeed the maximum of the pressure distribution is shifted in front of the contact zone, which can be explained by the geometry of the generated slot. Higher infeed leads to a geometric boundary in front of the contact zone, resulting in a rise of the dynamic pressure. If the measured pressure distribution is numerically integrated over the corresponding workpiece surface, the coolant pressure force component can be determined, taking some assumptions for the calculation into consideration [35]. Figure 4.4-18 (right) shows results of this combined calculation and measurement. A path with no infeed already leads to a normal force of 34 N, only generated by the coolant pressure. With increasing depth of cut the amount of this force component is, of course, reduced. However, still almost half of the normal force is attributed to the coolant pressure, even under deep grinding conditions of depth of cut $a_e = 3$ mm. This described method is suitable for investigating the influence of different coolant compositions. Especially the efficiency of additives can be evaluated, if the coolant pressure force component is known, and can be subtracted from the total normal force to emphasize the effect on the cutting, friction, and deformation component.

The use of special sensor systems for coolant supply investigations is a relatively new field of activity. First results have shown that these sensors can contrib-