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Development and Application of a Wheel Based Process Monitoring System in Grinding

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Abstract
As an advantage to conventional monitoring systems sensor equipped grinding wheels offer the possibility to gain information on the process status from direct measurements of physical quantities in the contact zone. This can be realized by the integration of small temperature and force sensors into segmented grinding wheels. A new thermocouple sensor concept was developed whose novelty is the continuous contacting of the thermocouple by the grinding wheel wear. Further tests where conducted using a piezoelectric sensor integrated into the grinding wheel. By this set-up, forces in grinding as well as in dressing processes were obtained. After assessing the system's capability for monitoring grinding and dressing processes tests in an industrial environment showed the reliability of the monitoring system which therefore may become the basis for a novel kind of process control in the future.

Keywords:
Grinding; Process Monitoring; Surface Integrity

1 INTRODUCTION

Facing increasing demands on manufacturing productivity quality control based on detection after the manufacturing process is no longer adequate. The pressure of costs is increasingly forcing the exploitation of the full potential of manufacturing processes.

Grinding is one of the most important manufacturing processes for high precision parts. Due to the complex characteristics of the grinding operation in-process measurements are very difficult. Up to now it is still challenging to apply in-loop quality control in grinding using in-process measurement techniques. Post process measurements and frequent interventions are causing the necessity to run the grinding process below its optimum capability in order to achieve the desired work quality.

A new approach to gain information about temperatures and forces of a grinding process is the wheel based measurement of process parameters using a telemetric data transmission. Preliminary investigations showed the ability of sensor equipped grinding wheels to determine these process parameters [1, 2]. Since these quantities are measured directly in the contact zone, where the material removal process takes place, these wheels can provide an advanced monitoring and controlling of the grinding process.

2 IN-PROCESS MONITORING AND CONTROL

In manufacturing operations in-process monitoring is a contemporary subject aiming on process cost reduction and work quality enhancement at the same time. In order to get detailed and reliable input parameters a multiplicity of investigations have been carried out to gain information about the actual condition of manufacturing processes.

The majority of process monitoring systems using tool based measurements were mostly implemented in geometrical defined processes as turning and milling. For example turning tools were equipped with conductor paths to detect wear, and resistive paths served to measure the temperature on the tool flank [3]. In milling operations e.g. force sensors have been used either in the tool itself or in the tool holder. A major difficulty is the realization of the signal transfer from the rotating tool to a data acquisition system. In addition to sensors, actuators have also been integrated into tools, which allow the adjustment of cutting edges [4, 5].

In grinding Acoustic Emission (AE) sensors have become state-of-the-art in monitoring grinding processes in industry [6]. While these systems typically use sensors mounted on the spindle bearing or at the spindle itself some attempts have been made to integrate AE sensors directly into CBN grinding wheels in order to monitor dressing operations and to detect chatter vibrations in grinding processes [7, 8]. In one set-up in addition to AE sensors a number of force sensors were integrated into a grinding wheel in order to detect out-of-roundness [9, 10]. Table 1 shows a survey of research work related to wheel based sensors in the last years.

Year	Authors	Design / Novelty
1993 [7] 2000 [8]	Inasaki et al. Inasaki, Karpuschewski et al.	Integration of AE sensor, signal transfer by slip-ring
2000 [9], 2002 [10]	Varghese, Malkin et al.	Integration of 11 force sensors, deriving AE-Signals from the same sensors, wireless telemetry
2002 [1], 2004 [2]	Brinksmeier, Böhm et al.	Integration of piezoelectric force sensors and film thermocouples, wireless telemetry

Table 1: Survey of wheel based sensor integration.

In addition to AE signals various process monitoring systems used in industry today are utilizing spindle power signals as control quantities. Both sensor types gain their information far from the contact zone and for this reason cannot evaluate the thermo-mechanical processes in the grinding arc of contact. This makes a direct temperature measurement still desirable. It can be realized by the integration of microsystem sensors in the grinding tool. By reducing the size of the sensors a fast response and high time resolution can be obtained. By this way, observance of the key parameters of the practical operation is enabled as closely as possible to the cutting area. Therefore process efficiency and tool status can be monitored independently from workpiece (material, shape etc.) or machining conditions (cooling lubricant supply, machine set-up parameters etc.).

3 SENSOR AND WHEEL SET-UP

A variety of approaches for temperature measurements in grinding processes is known. However, none of these overcomes the obstacle to be used in workpieces or grinding wheels in industrial application. In detail these are, on the one hand, necessary modifications of the test workpiece, which restrict these approaches to laboratory purposes. On the other hand, some detriments of the integration of conventional wire thermocouples in a grinding wheel are obvious: As the junction could be destroyed by the machining process, the sensor has to be placed at a defined depth from the abrasive surface. For this reason the response time of the integrated wire thermocouple is not fast enough to detect temperature rise in single workpiece contacts.

Measuring process forces in grinding quantitatively requires serious modifications of the machine tool design. Force sensors have to be integrated in the flux of force of the grinding machine, causing enormous costs and constraining these monitoring systems usually to laboratories.

For this reason a new set-up for in-process measurement of the temperature in the contact zone and the wheel based force measurement was developed. The sensors used in this system were developed in co-operation with the Institute for Microsensors, -actuators and –systems (IMSAS) at the University of Bremen.

The novelty of the approach is the continuously new-performed reconnection of the two elements of a thermocouple, which was initially introduced by Peklenik [11]. So far thermocouples of this design are only used for application in the workpiece [12, 13]. The wheel based application benefits from the modular set-up of segmented grinding wheels, which provides the necessary space for the integration of the sensor layer package The sensor is placed between the front end of two neighboring grinding layer segments in the anyway existing gap of glue as shown in figure 1. The upper margin of the layer is smeared across the insulation layer towards the second layer at each wheel revolution as the package passes through the contact zone. This causes the destruction of the previous connection as well as the immediate reconnection through the appropriate adjustment of the participating thermoelectric layers.

All temperature sensors used in the investigations were thermocouples of type K, a combination of Chromel (NiCr) and Alumel (NiAlMnSi) material. The maximum temperature to be measured by this sensor type is about 1350 °C. A response time of 40 ns measured during exposure to a laser impulse ensures the applicability in the grinding process. Several different sensor variants have been developed intending a maximum signal stability. Generally three sensor types can be distinguished: Thin film sensors, hybrid sensors and thermowire pairs.

Thin film sensors were processed by an evaporation technique of the Chromel and Alumel layer on a silicon substrate, in-between an insulation layer of SiON, produced by plasma enhanced chemical vapor deposition (PECVD). Looking at hybrid sensors only the Chromel and the insulation layer are deposited while the second material of the thermocouple is manually laid on the stack as a thin foil of 5 to 25 µm thickness.

Thermowire pair sensors are using the same mechanism for contacting the thermopartners. This sensor type consists of two conventional wires of type K material, separated by an insulation varnish. The wires are mounted in parallel in direction of cutting in the glue filled gap between two abrasive segments.

Comparing the different thermocouple types obviously the thin film sensors showed the shortest response time due to the extremely small volume of material to be heated. On the other hand, the stable signal behavior of the hybrid and thermowire pair sensors has to be pointed out.

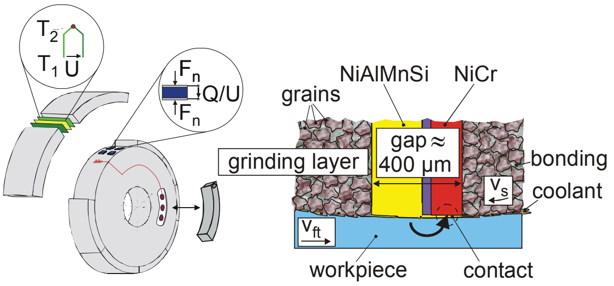


Figure 1: Integration of a thin film thermocouple and force sensors in the grinding wheel.

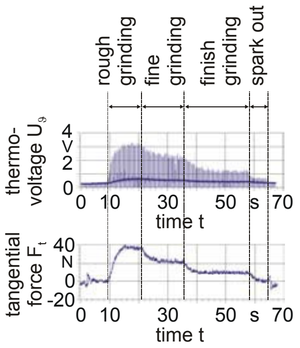
In addition to the temperature sensors described, a miniaturized force sensor was developed for the integration directly under a single abrasive segment. As the force signal is an impulse at each wheel revolution it is favourable to apply a piezoelectric sensing element.

For the integration into the wheel a piezoceramic force sensor of an area of 8x8 mm^2 was used. The sensitive piezoceramic was covered by gold sputtered ceramic layers which are connected to a charge amplifier. In preliminary tests the sensor package is installed under a cover, on which an abrasive segment was fixed. In order to assure a closed linkage between force sensor and abrasive segment even at higher wheel speeds a screw mechanism was used to apply a preload onto the sensor.

All tests were conducted using a telemetric system integrated into a ring attached to the grinding wheel's core. Several transmitters were used offering a bandwith up to 40 kHz. The power supply was realized inductively.

4 EVALUATION OF SENSOR CHARACTERISTICS

Several tests were conducted to evaluate the applicability of the different temperature sensor types. Testing the temperature sensors it was assumed that the variations of grinding power during a process cycle, displayed by the tangential grinding force, should be represented in the contact zone's temperature. To verify this behaviour a three-step grinding cycle in OD plunge grinding was performed. Afterwards the measured thermovoltage was compared to the tangential grinding force (figure 2).



process:
OD plunge grinding
material:
18 CrNiMo 7-6
(case hardened steel)
grinding:
grinding wheel: B 126 V
24 CO VA 2
d_s = 400 mm, b_s = 30 mm
a_p = 15 mm
v_c = 30 m/s
v_{fr} = 0.2/0.13/0.06 mm/min
v_{ft} = 31 m/min
coolant:
water based, Q_{CL}=10 l/min

Figure 2: Comparison of thermovoltage and tangential grinding force.

Obviously a mean rise of the abrasive layer's temperature can be observed by an increased base line of the thermovoltage signal. Moreover it can be seen that rough, fine, and finish grinding can be distinguished in the thermovoltage signal peaks as well as in the tangential grinding force. Even decreasing temperatures during spark-out can be monitored. Regarding all tests performed hybrid thermocouples and thermowire pair sensors seem to be most appropriate to be used in grinding process monitoring because of their good signal stability while the advantage of the thin film sensors is their quick response.

Similar experiments were carried out according to the process parameters in figure 2 to check the properties of the integrated normal force sensor.

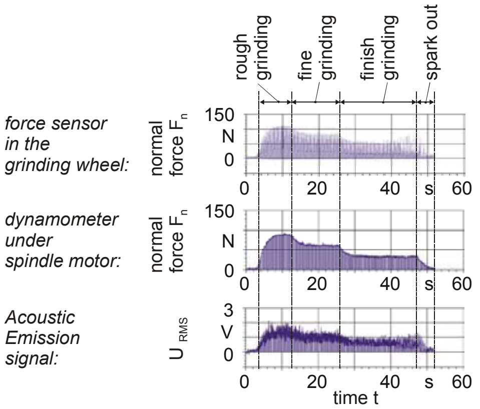


Figure 3: Comparison of grinding forces and AE-signal.

Normal force signals measured by dynamometers integrated into the machine tool and AE signals acquired by a commercially available monitoring system were used as reference. Figure 3 shows a result for a three-step grinding cycle. It can be seen that process steps rough and fine grinding can be clearly distinguished by the wheel integrated force sensor as well as regarding the conventional piezo dynamometer. Regarding the AE-signal an increase can be observed at the end of the finish operation and during the spark out step, which is caused by grinding chatter. By the force sensor integrated into the grinding wheel a higher signal amplitude was registered at the same time, while this effect cannot be seen in the static force signal.

The experimental investigations confirm the applicability of both, temperature and force sensors, to monitor grinding process behaviour.

5 WHEEL BASED MONITORING OF PROCESS QUANTITIES

The investigations were focused on the identification of correlations between the process values thermovoltage and grinding forces, and the surface integrity after grinding. For this reason grinding tests with an increasing depth of cut during a single workpiece revolution in OD creep feed grinding were performed. The surface layer condition was evaluated by etch inspection on the circumferential face and measurements of the surface hardness in a pitch of 20 °, which approximately corresponds to steps in depth of cut of 11 µm.

Figure 4 shows an exemplary result of these grinding tests. As expected the tangential grinding force, representing the grinding power, rises almost linearly with increasing depth of cut. Reaching a depth of cut of approx. 110 µm the surface hardness drops. The surface layer etch inspection however indicated a damage of the material only at a higher depth of cut of about 130 µm.

Focusing on the wheel-based thermovoltage measurement it can be seen that the temperature remains nearly constant up to a depth of cut of about 100 µm. Exceeding this value the thermovoltage shows a steep rise to a maximum of about 4.5 V. This point correlates to the changes in the workpiece surface layer described above. It is assumed that this behaviour is caused by coolant film boiling. This of the workpiece surface layer. This test demonstrates the ability of the wheel-based temperature measurement to detect influences of the grinding temperature on the workpiece surface layer.

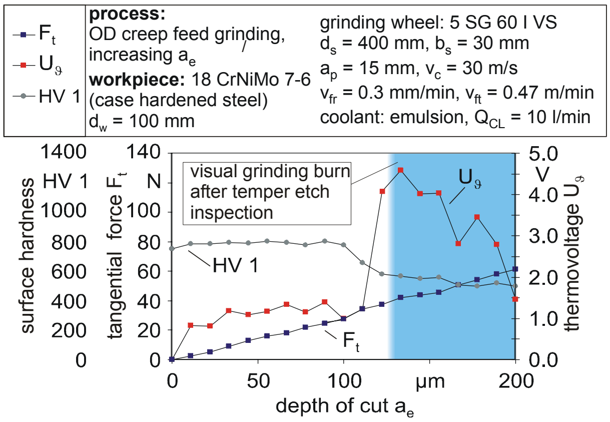


Figure 4: Tests with increasing depth of cut to detect grinding burn.

6 MINIATURIZED SET-UP OF SENSOR INTEGRATED GRINDING WHEEL

As the wheel design used in the preliminary investigations described above suffers from severe modifications of the grinding wheel and space required for the integration of the components of the telemetric system into the grinding machine, a miniaturized set-up had to be developed aiming the use at industrial processes. Time and cost consuming modifications of the machine tool periphery should be minimized.

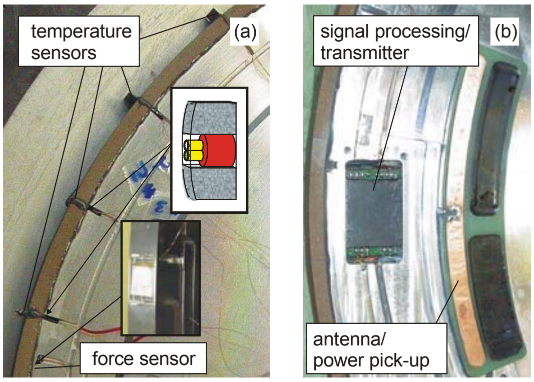


Figure 5: Integration of sensors and telemetric system into the grinding wheel.

Figure 5 (a) shows the integration of four different temperature sensors, two hybrid and two thermowire sensors, and one piezoelectric force sensor into a vitrified CBN grinding wheel. The force sensor was integrated into a cavity in the wheel core while the abrasive segment was stuck on using a preload. On the right hand (b) of figure 5 the new telemetric system can be seen. The signal processing and transmitting unit able to transmit two temperature and two force channels at a bandwidth of 100 kHz is small enough that it can be integrated into the core of a grinding wheel featuring a width of 10 mm. Only the power pick-up / antenna device protrudes from the wheels core. A ring-shaped stator integrating the primary coil and the receiving antenna is fixed in the ginding wheel cover of the machine tool.

7 INDUSTRIAL APPLICATION

The wheel set-up was used in an external cylindrical grinding operation of bearing rings in the finishing line of a bearing manufacturer.

The system was integrated into an OD grinding machine. Due to the simplified setup, modifications of the machine tool could be reduced to tap holes for fixing the stator of the telemetric system.

During the tests several series each of 50 bearing rings were machined, none of them suffering from defects associated with the integrated sensors. A dressing operation before each grinding cycle ensured comparable standards of temperature sensor and wheel topography condition. Temperature signals and normal force signals of each cycle were recorded as well as the AE signal acquired by a conventional AE monitoring system as a reference value. The top of figure 6 shows a plot of temperature and force signals at a single contact of sensors and workpiece. The temperature signal is characterized by a steep rise when the sensor enters the grinding arc of contact, followed by an exponential decrease. The temporal delay between the signals is caused by the sensor positions as illustrated in figure 5. The graph in figure 6 at the bottom shows the progression of the peak values of thermovoltage and force signals as well as of the reference AE signal. Since reliable calibration methods for temperature and force measurements in extreme short time ranges (≤ 0.01 ms) were not available, only voltages and no absolute values for force and temperature are given. During the first cycles after dressing the signals start at a high level due to wheel topography. Obviously wheel topography after the dressing causes relatively high values of thermovoltage and normal force in the first grinding cycles. Looking at the reference AE measurement the same effect can be observed. After grinding of the first 5 workpieces the values measured remain nearly constant. While the normal forces scatter around a mean value during the series, a further decrease of the thermovoltage corresponding to the reference AE signal develops up to cycle no. 20. Consecutively a steady state of the thermovoltage signal can be noticed, while the AE signal still slightly tends to decrease. The excellent correlation of the thermovoltage- and the AE-signal shows the sensitivity of the integrated thermocouple sensor.

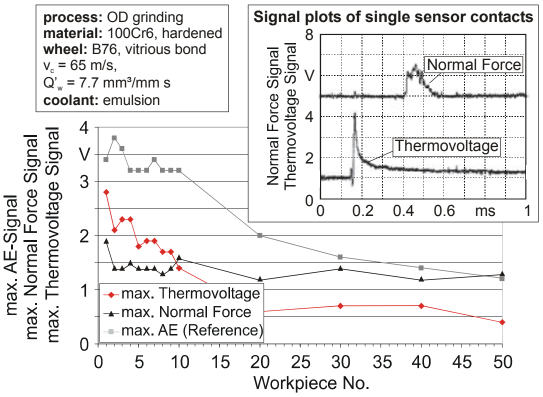


Figure 6: Normal force and thermovoltage signals during grinding of bearing rings.

During the tests a series of 1,500 workpieces was machined without failure of the measurement system. These tests have shown the potential of the sensor integrated wheel to monitor industrial grinding processes in harsh environments.

8 CONCLUSION AND OUTLOOK

The development of microsensors for a wheel based measurement of temperatures and forces in grinding processes was outlined. Film and thermowire thermocouples have been produced, that fulfill the required characteristics for grinding purposes. Miniaturized piezoceramic force sensors were integrated under discrete abrasive segments saving complex changes to the wheel geometry. Industrial application of the system demonstrated the reliability of the wheel based monitoring system under practical conditions. The wheel integrated force sensor demonstrated an easy implementation of force measurement in grinding without complex adaptations of the machine tool.

In the future, thermovoltage and temperature measurements respectively may become a tool to control the quality of workpiece surface layer in the industrial production. As an example a measuring system will provide the process data that could be used for a real-time closed-loop process control. The integration of a greater number of sensors could enable the analysis of dynamic effects.

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