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Impact of Sensor Equipped Grinding Wheel and its Prospects

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Abstract: The in-process measurement and observance of grinding forces near to the contact zone is a matter of concern in most production grinding operations. To optimize the acquisition of process forces and to compensate the lack of sufficient information about the process status, the incorporation of a force sensor inside the tool is proposed in this paper. It represents the first step of a tool development with integrated miniaturized sensors assessing the main design factors of the tool. The analysis has proved to be useful during the first development phase as it leads to a minimization of the number of tests for the selection of the sensoric principle, the location of sensor integration, and the final tool design.

Keywords: Grinding, Sensor Integration Impact of static and dynamic loads, variation of loads and forces.

I. INTRODUCTION

Caused by the difficult accessibility of conventional measuring techniques various methods have been developed so far for the direct and indirect measurement of process parameters which decisively influence the grinding operation [WES 94]. To simplify matters, most of the sensoric devices were installed in the machining environment far away from the contact area to monitor the grinding process [BYR98]. Consequently, they are not well suited to create reliable data during machining corresponding to the actual machining conditions [TON 88], see Figure 1.

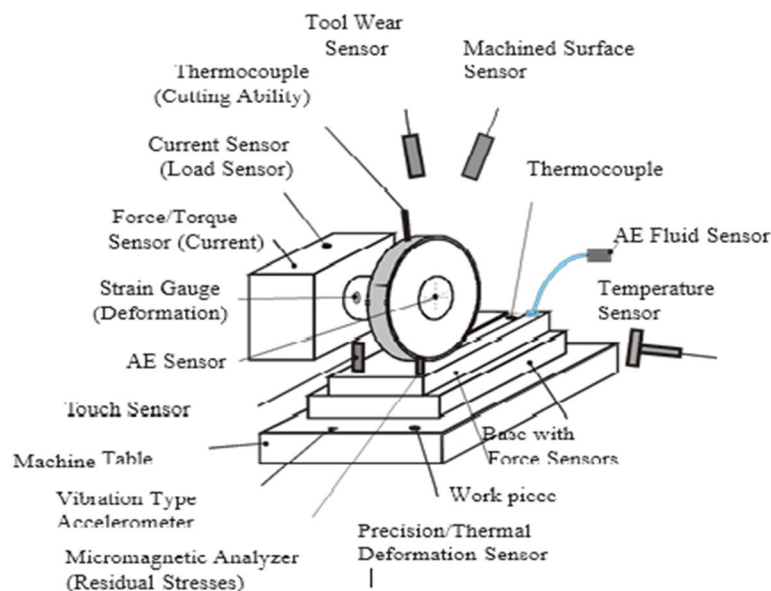


Figure 1. Arrangements of sensors in the machining environment

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Because of the need to deliver sufficient and reliable information from the machining point, the integration of sensors inside the grinding wheel was proposed [INA 93] [KOJ 90] [GOL 95]. Due to their close proximity to the contact zone where the process parameters decide about the quality of the work piece, sensor equipped grinding wheels could form the basis for new grinder systems that have the potential for significantly increased production rates and improved quality. However, before a grinding wheel with complex miniaturized sensor and telemetric components is developed, it is recommended to prove the feasibility of such a tool system. As a matter of fact, the integration of sensors (and electronic devices for signal transmission) has to cope with special restrictions of the rotating tool system. Keeping in mind that the sensors have to be positioned preferably at the tool periphery in close proximity to the contact zone, rotational acceleration determines the mechanical structure and sensitivity of the sensor type. On the other hand thermal influences and signal length have to be considered according to the fast circumferential speed of the tool. Up to now, just a few approaches have been proposed which directly extract information out of the rotating grinding wheel by integration of sensoric devices, see Figure 2. Most of them aimed at measuring the temperature in the contact zone by measuring the thermo-voltage of a thermocouple arrangement. Moreover, basic approaches for in-process monitoring of process forces out of the grinding wheel were proposed, taking into account strain gauges or acoustic emission sensors.

In the following, the experimental and analytical characterization of a grinding wheel with an integrated piezo-electric force sensor is presented. The experimental characterization is performed under two aspects. One is to prove the feasibility of the sensor principle, the other is to demonstrate the benefit of a sensor equipped grinding wheel compared to a conventional measuring method. The comparison between a conventional measuring method and the sensor equipped grinding wheel is demonstrated for the case of tool fracture. Contrary to the approaches of Figure 2, the sensor of this study is integrated below one segment of the abrasive layer to measure directly the normal, tangential and axial forces. Therefore, it is necessary to verify the location of the sensor for the development of a miniaturized sensor

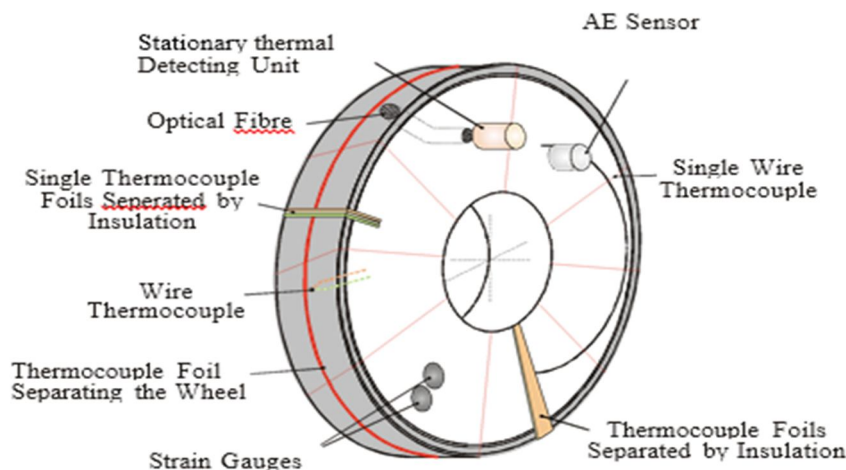


Figure 2. Integration of sensors in the grinding wheel

The main objective of the analytical characterization is the assessment of the influences of the modifications at the grinding wheel. The modifications imply the assembled telemetry holding and the interference into the basic core for integration of the sensor and the core segment. The gain of the analytical approach is that the results are used as guidelines for the next design steps, reducing the need for real testing. For this purpose, FEM is used and static and dynamic calculations are performed in order to approach the problem

II. EXPERIMENTAL SET-UP

The demonstrator consists of a vitrified segmented CBN grinding wheel ($d_s = 400\text{mm}$, $b_s = 30\text{mm}$) with an aluminum core and an integrated piezo-electric force sensor. For wireless power supply and transfer of the measured data from the tool-integrated sensor to a stationary receiver inside the machining chamber, a telemetric system was realized. Contrary to battery-powered tools, where the durability of power supply is restricted, this transmission is suited best with regard to an application in industry

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where a long service life of the tool is demanded. The FM telemetric unit consists of a preamplifier, V/F-converter, multiplexer, and transmitter. These components are placed inside a ring-holding which is coupled with the rotating wheel. Receiver, de multiplexer, filter, and signal conditioning modules are arranged outside the tool. The distance between primary and rotating coil is adjusted below one millimeter to reduce the possible influence of chips or lubricants. After calibration of the sensor all signals were recorded during machining and subsequently processed using PC.

III. CHARACTERISTICS OF THE SENSOR EQUIPPED GRINDING WHEEL

Contrary to the conventional force measurement method which is oftentimes characterized by a stationary force base under the work piece, the arrangement of a force sensor inside the grinding wheel delivers more exact force component affecting the wheel. The comparison between the work piece based and the tool based force measurement is illustrated in **Figure 4**.

Additionally, it has to be pointed out, that due to the sensor integration the sensor is exposed to one fast load change per tool revolution. The load change is caused by the interaction between the abrasive segment which is connected to the sensor and the work piece, see **Figure 5**.

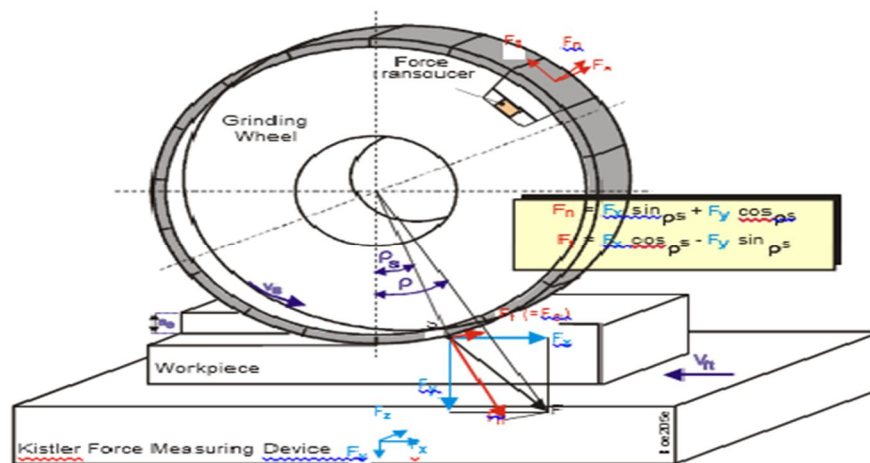


Figure 4. Interrelationship between stationary measured grinding forces and grinding forces measured by the wheel itself.

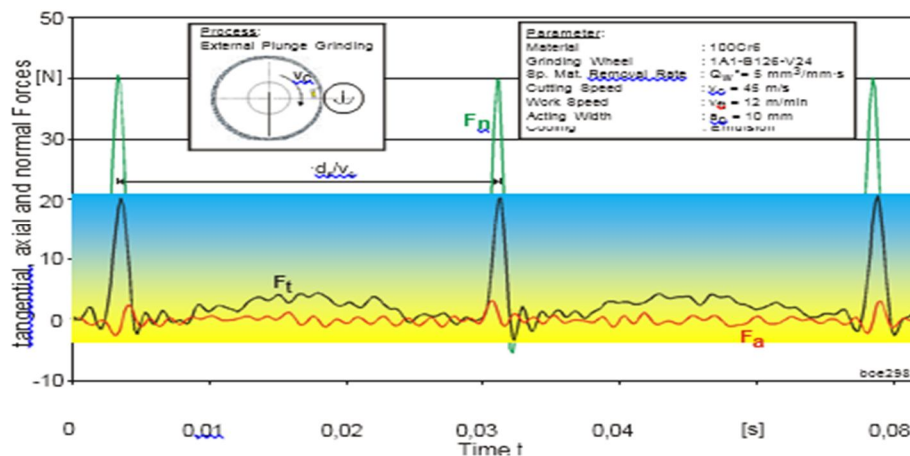


Figure 5. Grinding forces measured by the grinding wheel.

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IV. COMPARISON OF CONVENTIONAL FORCE MEASUREMENT AND FORCE MEASUREMENT OF THE WHEEL ITSELF DURING TOOL BREAKAGE

The advantage of a sensor equipped grinding wheel was demonstrated in experimental studies for contact detection, dressing, and grinding (external plunge grinding and surface grinding) [BRI 98] [BRI 99]. Here, the comparison between the force measurement by the rotating tool and the stationary force measurement is presented for the case of tool breakage. In many grinding operations, machining as closely as possible to the allowable load constraints can be desirable for an enhanced grinding productivity. But when the process forces reach a certain limit, the wheel engagement is usually accompanied with some malfunctions such as wheel loading, chatter vibrations, or in the worst case with tool fracture. Here, some sites at the peripheral are affected which can result in breaking out of pieces of the abrasive layer. In such a case, fast recognition and action is necessary, because this behavior results generally in work piece or even spindle damage and consequently in a loss of production times.

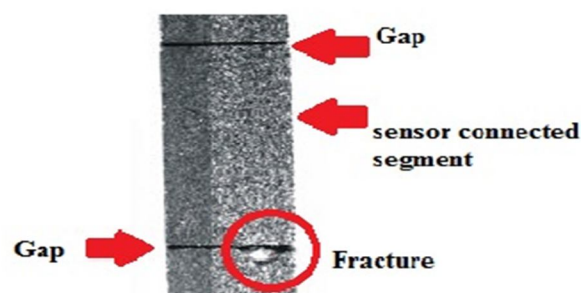
In order to prove the benefits of a sensor equipped grinding wheel for tool fracture observance, the specific grinding force was increased in a test series. During an external plunge grinding operation with a grinding force F_n of 120 N, which corresponds to $F'_N = 15 \text{ N/mm}$, breakage of the abrasive layer occurred after approximately 14 seconds. In Figure 6 the development of normal forces (conventional force measurement method versus force measurement out of the tool) is compared. The site of fracture was observed near the gap between the sensor connected segment and the basic core (see Figure 6). The following operation time was characterized by an unstable grinding process accompanied by increasing chatter and vibrations. In spite of the spindle balancer which was attached to the spindle end, the vibrations could not be compensated. Therefore, the human operator decided to initiate the emergency stop at approximately 14.8s to retract the spindle. From this point of time the normal force decreased to a minimum.

Comparing both progressions of normal forces, the difference between both methods is obvious: while the stationary measuring system measures a smooth increase of the normal grinding forces and also a variation of normal forces after the breakage, the integrated force sensor delivers a drastic drop of the normal forces between 14.2s and 14.8s. Only after the initiation of the emergency stop both progressions of forces present the habitual coincidence.

The missing signals from the incorporated sensor suggest that there is a kind of malfunction of the measuring system. Yet considering that the sensor signals of the integrated force sensor rely heavily on the interaction of the sensor connected segment with the work piece, it can be concluded that no interaction between the segment and the work piece took place. This assumption was confirmed by the inspection of the chatter marks which were distributed over the circumferential of the grinding wheel. It was found that the chatter marks did not affect the sensor connected segment. It follows that during the chatter; the sensor connected segment had no contact to the work piece and, as a consequence, was not able to detect any engagement. From the viewpoint of the integrated force sensor the time between 14.2 s and 14.8 s can be characterized as idle grinding.

The comparison of both signals reveals that the integrated sensor is able to detect chatter (engagement and disengagement of the sensor connected segment) more distinctly compared to the slow increase of the normal forces delivered by the stationary measuring unit.

Grinding Wheel
1A1-B126-V24
$v_c = 40 \text{ m/s}$, $n_s = 2150 \text{ min}^{-1}$
Workpiece
Material 100Cr6
$d_w = 69.5 \text{ mm}$
$Q_w = 15 \text{ mm}^3/\text{mm}^3$
Cooling Lubricant
$q_{zss} = 20 \text{ l/min (Emulsion)}$



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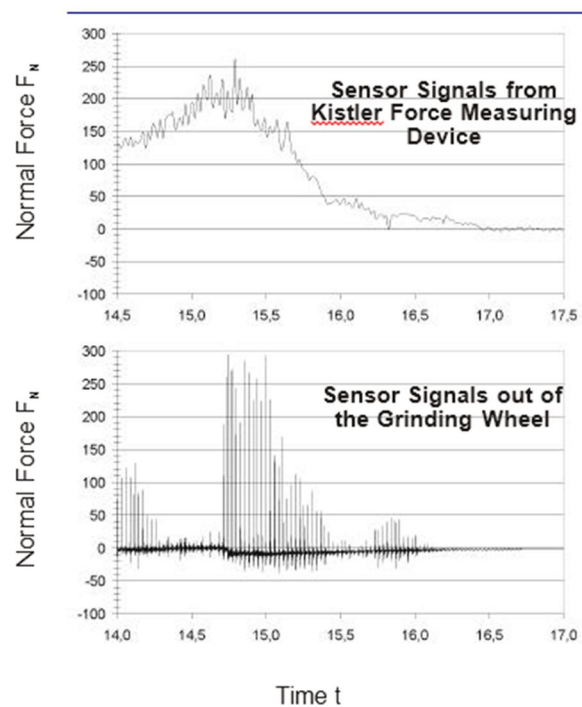


Figure 6. Comparison of normal grinding forces measured by the stationary Kistler measuring device and by the tool itself during external plunge grinding.

A. The influence of the static loads

The static loads on the tool system result from the process forces, the masses of the components, and the centrifugal load. The static deformations at the tool depend on the elastic characteristics of the material and occur due to the applied loads at any given time. To evaluate the tool behavior, the FE method is used. The studied case respects the conditions during machining with the worst magnitude and direction of the loads at the most critical working point. As a result of the calculation, the shape of the modeled structure can be visualized, see [Figure 7](#), so that the importance of the deformation on the work result can be assessed.

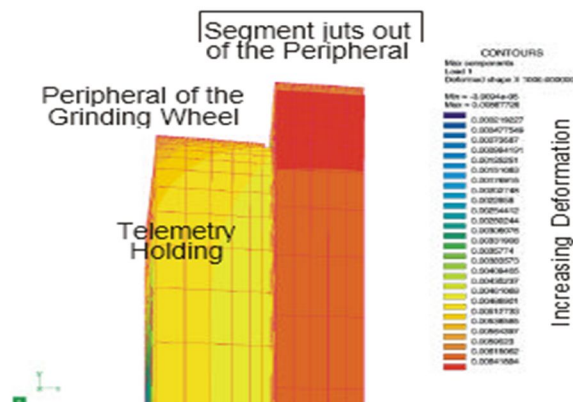


Figure 7. Affection of the tool system by rotational forces

The static calculations clearly show the influence of the sensor integration and of the adaptation of the telemetry ring. The adaptation of the telemetry ring results in a deformation of the tool system under centrifugal forces. [Figure 7](#) illustrates the deformation at

$= 222s^{-1}$, which corresponds to a cutting speed of $v_c = 45$ m/s. Here, the greatest deformation amounts to $6.68\mu m$ and indicates

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that dressing of the outer peripheral becomes necessary before the experimental investigations to guarantee a cylindrical shape of the wheel peripheral.

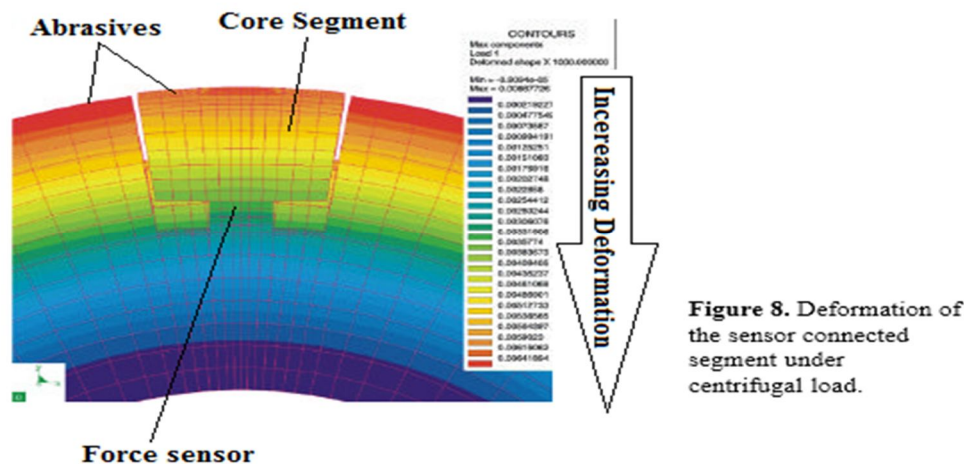


Figure 8. Deformation of the sensor connected segment under centrifugal load.

In **Figure 8** the influence of the centrifugal force on the core segment is illustrated. The visualization of the calculation points out that due to the mass of the core segment which is bound to the sensor the core segment is subject to radial expansion. This is a critical factor which disturbs the rotational behavior of the tool. Therefore, the masses which are connected to the sensor must be drastically reduced in the next development step.

To investigate the deformation of the core segment, process forces were applied to the core segment to simulate the load of the grinding process. Figure 9 shows the scaled up deformations of the core segment and the location where the tangential, normal and axial forces were applied. The simulation clearly shows that by applying high static loads to the core segment the core segment does not abut on the basic core, which would automatically limit the measuring range of the rotating sensor. Nevertheless, the significant deformation of the outer peripheral must be avoided and it is obvious that by shortening the distance between sensor and abrasive segment a significant improvement can be expected.

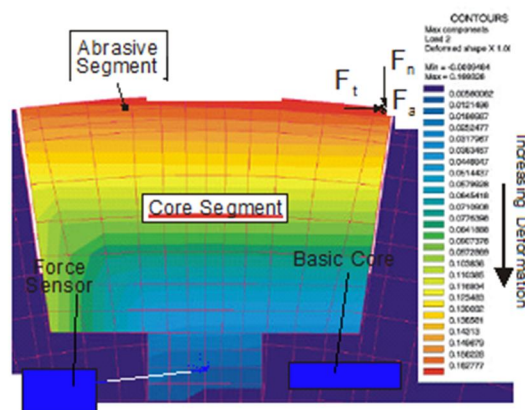


Figure 9. Deformations at the sensor connected segment ($F_n = 3000\text{N}$, $F_t = 1000\text{N}$, $F_a = 1000\text{N}$, $v_c = 10\text{m/s}$)

B. The influences of the sensor integration on the dynamic wheel behavior

Apart from the static loads the rotating tool is subject constantly to changing dynamic loading, which must also be taken into account. When the grinding wheel is under pulsating excitations, the tool will vibrate mainly at one of its natural frequencies. Hence, whenever the frequency of excitation is in the same range as a natural frequency of the wheel, large vibration effects are

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most likely. This is also the case when the repetition rate of a pulsating excitation coincides with the natural frequency. Bearing the requirements of the grinding tool for the surface quality of the work piece in mind, the vibrational deflections at the tool must be kept under acceptable limits.

A dynamic calculation was performed in order to draw conclusions about the structural behavior of the tool system. The interference into the grinding wheel must cause only minimal distortion in order to achieve a grinding result which is not worse than the result obtained with conventional tools. As a result of the simulation Figure 10 shows that the interference into the basic core drastically influences the natural modes of the tool. This feature must be respected for the further improvement.

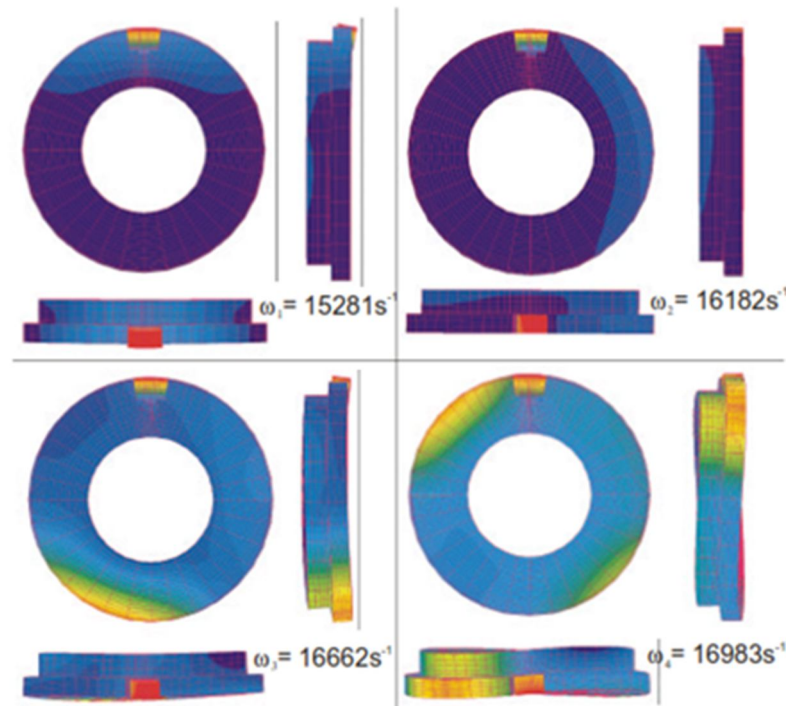


Figure 10. Calculated Eigen modes of the tool system

V. CONCEPT OF A SENSOR EQUIPPED GRINDING WHEEL WITH MINIATURISED FORCE SENSORS

Apart from the experimental feasibility study, the main intention of the simulation was to find a suitable concept for a sensor equipped grinding tool with a minimum of relative displacement under static and dynamic loads. With the input of the visualized simulation results the main weak point of the demonstrator is seen in the isolated core segment which influences the deformations under static and dynamic loading. In a further improvement step, this weak point must be the focus of optimization.

Figure 11 illustrates the next approach which sums up the experiences from the experimental and analytical investigations. Based on the verification that the location of the force sensor under one abrasive segment is suitable for the direct measurement of the grinding forces, the sensor is miniaturized to a thin film array and positioned in the gap between abrasive segment and basic core. This gap is normally filled with glue but is expected to deliver enough space for this kind of sensor. Hence, the interference into the basic core as a result of the sensor integration is reduced to a minimum. Compared to the demonstrator tool, the ring holding for the telemetry is eliminated and the basic core is used to assimilate the single modules. Antenna and coil are attached to one side of the basic core.

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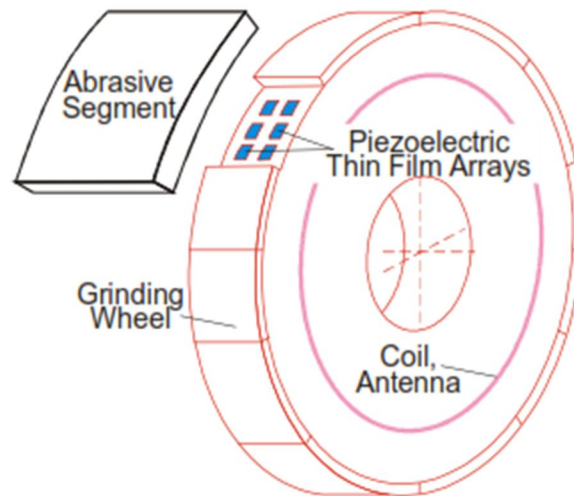


Figure 11. Second approach of the development of a force sensor equipped grinding wheel

VI. PROSPECT OF SENSOR EQUIPPED GRINDING WHEELS

The development of an intelligent grinding wheel could be successful to such an extent that it becomes possible to connect the signal from the grinding wheel via a machine tool interface to the control unit of the machine tool. Figure 12 lists all important elements that are necessary to build a new grinder system. In addition to the rotating sensor and telemetric unit, a stationary coil is necessary which must be connected inside the machining chamber. After wireless transmission to the stationary receiver the sensor signals must be prepared for the interface to the automatic control of the machine tool. Other than the above presented force sensor, sensors for the measurement of process temperature and tool vibrations are highly desirable to enhance the functionality of the tool [AHR 99]. This kind of sensor fusion could then open up new degrees of freedom in the observance of grinding processes. Nevertheless, Figure 12 shows the potential of the intelligent grinding wheel, which is part of an “intelligent controlled grinding process.”

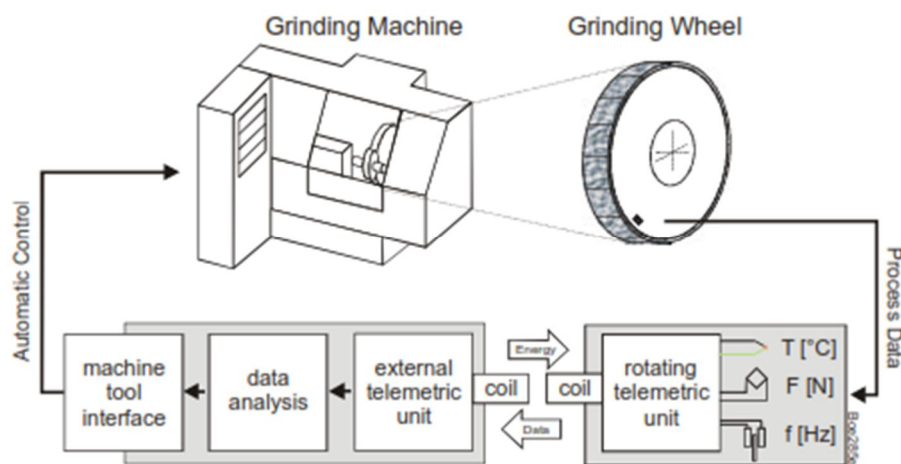


Figure 12. Sensor equipped grinding wheels as an element of an “intelligent grinding process”

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VII. CONCLUSIONS

To install an optimal set-up of process parameters, the full knowledge of the working conditions inside the contact zone between grinding tool and work piece is required. Sensor equipped grinding wheels are suited best to deliver measured data because of the proximity between sensor and measuring point. In this regard, the first development step of an intelligent grinding tool has been presented together with an analysis of the influences of the force sensor and telemetry integration.

The static and dynamic influences of the adapted or integrated components were simulated by means of FEM analysis. Therefore, it must be pointed out that for the industrial application of the sensor equipped grinding wheel a drastic miniaturization of the sensoric and telemetric components must be achieved.

The investigations demonstrate that a force sensor located below an abrasive segment allows to measure in-process normal, axial and tangential grinding forces. The advantage of this kind of force measurement compared to the conventional force measurement method was demonstrated for the example of tool fracture. By wireless transmission the sensor data is principally available for the control system of the machine tool.

Nevertheless, the investigations show that such a wheel can be a powerful evaluation aid to form the basis for a new grinder system that would allow significantly increased production rates and improved quality.

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