Potential and challenges of tool condition monitoring in gear hobbing

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Abstract
Due to its high productivity, gear hobbing is one of the most frequently used manufacturing processes for the soft machining of cylindrical gears. One of the main objectives of an optimized manufacturing process is to maintain the required component quality while minimizing manufacturing costs. In both cases, knowledge of the tool wear is of great importance. Tool Condition Monitoring (TCM) provides a methodical approach to tracking tool wear during the process. In this report, various sensors are investigated with regard to their potential for TCM. Fly-cutting and hobbing experiments were conducted for this purpose. The signal data recorded during the tests were processed using high-pass filters, Hilbert transforms and Fast Fourier Transforms (FFT) in the time and frequency domain and evaluated according to various parameters. Based on the results, statements were made about the relationships between signal data and process conditions. For a precise evaluation of the tool condition, the combination of several sensors is necessary. In particular, the tool-side-mounted acoustic emission and acceleration sensors in combination with the power sensor and the airborne sound sensor showed increased amplitude values with increased wear. For the acceleration signals it could be shown that higher orders reacted more sensitively to increased tool wear. For the workpiece-side-mounted sensors, no meaningful results could be obtained due to the large distance to the cutting zone.

1 Introduction
Gear hobbing is one of the most frequently used manufacturing processes for soft machining of cylindrical gears due to its high productivity. The objective of an optimized manufacturing process is to maintain the required component
quality while reducing manufacturing costs. As the component quality decreases with increasing tool wear, the tool has to be replaced after a certain wear criterion has been exceeded. However, replacing the tool before a critical state of wear has been reached leads to additional costs. Knowledge of tool wear is therefore indispensable for an optimal utilization of tool life. Tool Condition Monitoring (TCM) provides a methodical approach for detecting critical wear during the manufacturing process. TCM is defined as the use of sensors to monitor and predict tool condition directly and/or indirectly [1]. Different types of sensors can be used in combination for TCM, for instance: acoustic emission, airborne sound and acceleration sensors. The main causes of occurrence can be attributed to material deformation, friction during chip formation, tool and chip breakage and vibration [2–4]. By evaluating the signal data under consideration of the process characteristics, the tool wear can be predicted. The recorded signals can be evaluated in the time, frequency or time-frequency domain, whereby a signal transformation is necessary for evaluation in the frequency and time-frequency domain [5]. With the help of characteristic values formed from the signals, the tool condition can be determined [5]. In the past, TCM has been scientifically investigated especially in turning [3–8], milling [9, 10] and drilling [11]. In gear hobbing only a few studies have been published to determine the influence of tool wear on spindle performance [12–14]. A scientific study of the potential of using different sensors in hobbing has not yet been carried out.

A variety of methods has been developed for the use of TCM, which has been classified into direct and indirect methods [2, 5, 15, 16]. In the direct methods, also called offline measurement methods, the value of a wear parameter is determined directly, for example by optical methods [5]. The disadvantage is the restricted practical applicability due to the limited accessibility in the process, the mostly insufficient illumination and the use of cooling lubricant in some manufacturing processes [5, 16].

Compared to the direct methods, the indirect methods have been increasingly scientifically investigated [4]. By indirect methods, also called online measuring methods, parameter values are determined and correlated with the wear [5, 15–17]. Mainly the cutting force, machine acceleration, sound, acoustic emission and spindle power were used [2, 4, 5, 16, 18]. Advantages of the indirect methods compared to the direct methods are better practical applicability due to higher flexibility and the detection of occurring changes of the tool condition during machining [5, 16]. Disadvantageous are the less accurate results due to the partly difficult assignment of the measured variable to the tool condition compared to the direct methods [5, 16].

A universal TCM method for all machining processes has not yet been established [7, 9, 10, 15]. The complexity of machining processes makes the application of TCM very specific, which means that there is a need for further research in this field [5, 10]. The analysis of several signal variables by combining different sensor types in the process provided conclusions about various process influences. By using only one sensor, the detection of signal errors caused by external influences is more difficult [2]. A sensor combination was described as a very useful approach for future research [4, 6, 8].

The presented scientific studies show the potential for optimizing manufacturing processes by means of TCM. However, so far the investigations were carried out mainly for turning processes. Due to the complexity of the gear hobbing process, no universal method for tool monitoring can be used. The application to the hobbing process has only been scientifically investigated to a limited extent. Knowledge about the influence of the process parameters on the sensor signals is not yet available. How far the influence is reflected in the signal in the time, frequency as well as in the time-frequency domain is also not yet known. The objective of this study is to investigate the potential and challenges of TCM for hobbing. The approach is divided into design of experiments, test execution and evaluation of the test results.

At first, various sensors which achieved good results in the TCM of other processes were mounted in a gear hobbing machine. In addition, the process influencing parameters were defined. Afterwards, fly-cutting tests and hobbing tests were carried out. In the fly-cutting tests, the focus was on the detection of tool breakage. In the hobbing tests, the influence of wear and parameters on the signal data was analyzed. Finally, signal data were recorded in a small batch of gears in order to verify the knowledge gained in production. The software Labview and Optimizer4D were used to record the signal data. The signal data obtained was processed and analyzed in the final step of the procedure. Various signal processing methods were used for this purpose. From the signal data obtained, characteristic values were determined, on the basis of which the tool condition and the influence of the process parameters could be derived. The knowledge gained made it possible to determine the potential of the TCM in gear hobbing.

2 Experimental setup and material characterization

The tests were carried out on the gear hobbing machine Liebherr LC180. The test setup, with regard to the positioning of the sensors, was identical for the fly-cutting and the hobbing tests, cf. Fig. 1.

The sensors used were an airborne sound sensor ROGA RG-50 (1), two acceleration sensors from PCB of type
Fig. 1 1 Sound sensor (ROGA RG-50 Microphone) 20kHz; 2 Tool; 3 Workpiece and clamping system; 4 Acceleration sensor on tool side (PCB 622B01) 0.2–15 kHz; 5 Acoustic emission sensor on tool side (QASS AE-sensor) 100 MHz; 6 Acceleration sensor on work side (PCB 622B01) 0.2–15 kHz; 7 Acoustic emission sensor on work side (KISTLER 8152) 50–500 kHz; Hobbing machine: LIEBHERR LC with Sinumerik 840d sl

622B01, which were attached to the tool-side (4) and workpiece-side (6), an acoustic emission sensor from Qass (5), which was placed to the tool-side and an acoustic emission sensor from Kistler of type 8152 (7), which was attached to the workpiece-side. Furthermore, the machine control Sinumerik 840d sl was used for monitoring the spindle power. The acceleration sensors, the workpiece-side acoustic emission sensor and the airborne sound sensor record vibrations in kHz domain. The acoustic emission sensor on the main tool bearing records signals in MHz domain, which allows a more precise investigation of short time intervals, but also makes data processing more challenging due to the high volume of data.

For the evaluation of the signal data, a short time interval of a few seconds was chosen in order to be able to evaluate the data with conventional software and hardware. The time interval was placed in the middle of the process, where the tool is in the full cutting area.

During the tests, various tool and workpiece geometries as well as materials were used. The selected materials were chosen because they are frequently used in industry. Fig. 2 shows the microstructure and Table 1 contains the characterization of the workpiece materials used.

The soft state case-hardening steels 20MnCr5 and 16MnCr5 had a ferritic-pearlitic microstructure and were used for the hobbing tests. A martensitic structure was

Table 1  Chemical composition, brinell hardness and tensile strength of workpiece materials

| Material       | C /wt% | Si /wt% | Mn /wt% | P /wt% | S /wt% | Cr /wt% | Mo /wt% | Ni /wt% | HBW 2.5/62.5 | Rm /MPa |
|----------------|--------|---------|---------|--------|--------|---------|---------|---------|--------------|---------|
| 20MnCr5        | 0.20   | 0.24    | 1.14    | 0.016  | 0.022  | 1.06    | 1.06    | 0.026   | 170          | 575*    |
| 16MnCr5        | 0.184  | 0.279   | 1.08    | 0.0105 | 0.026  | 0.92    | 0.045   | 0.098   | 174          | 585^    |
| 42CrMo4        | 0.44   | 0.24    | 0.73    | 0.008  | 0.029  | 1.09    | 0.201   | 0.147   | 320          | 1000^   |
| EN-GJS-700-2   | 3.50   | 3.04    | 0.6     | 0.014  | 0.009  | 0.06    | 0.009   | 0.04    | 310          | 700^    |

*Revaluation ISO 18265—A.1
^Revaluation ISO 18265—B.2
"Manufacturer information
documented for the alloyed tempered steel 42CrMo4. The cast iron EN-GJS-700-2 had a pearlitic base structure with embedded nodular graphite. The tempered steel and the cast material were used for the fly-cutting trials. The higher strength materials were used in the fly-cutting tests to achieve fast advancing wear to be able to study the signal data in catastrophic wear and tooth breakage.

The hardness was measured on the workpiece surface and converted into the corresponding tensile strength $R_m$ according to DIN EN ISO 18265 [19]. The case hardening steel 20MnCr5 had the lowest hardness of 170 HBW 2.5/62.5 compared to the other materials. The highest hardness, 320 HBW 2.5/62.5, was measured on the alloyed quenched and tempered steel 42CrMo4.

3 Potential of breakage detection in fly-cutting trials

In the following, the potential of the described sensors with regard to breakage detection is investigated. In fly-cutting tests, tool failure due to breakage or catastrophic tool wear were deliberately provoked. The recorded signals were then analyzed with regard to their change in the time, frequency and time-frequency domain.

3.1 Design of experiments

The fly-cutting tests were carried out with a WC-Co K30 carbide tool and a powder metallurgical high speed steel (PM-HSS) S390 tool. The different tool substrates were chosen to investigate the different wear mechanisms. PM-HSS cutters usually reach the end of their service life due to crater wear. Carbide cutters, on the other hand, have a higher temperature resistance and wear abrasively. They break under too high load. One test point was investigated for each tool. A module $m_n = 2.557$ mm gear with a number of teeth of $z_2 = 39$ was selected for the gear geometry. This represents the dimensions of a typical automotive gear. The investigations are therefore relevant for the industry. The tools used were also selected according to the industrial state of the art. The geometries of tool and workpiece used

![Image](https://example.com/image1.png)

**Workpiece**

| Material: 42CrMo4 |
|------------------|
| $z_2 = 39$ |
| $\beta_2 = 23^\circ$ |
| $b_2 = 30 \text{ mm}$ |
| $d_{a2} = 116.2 \text{ mm}$ |
| $d_{l2} = 100.0 \text{ mm}$ |

**Tool**

| Substrate: S390 |
|----------------|
| $m_{n0} = 2.557 \text{ mm}$ |
| $a_{n0} = 17.5^\circ$ |
| $h_{ap0} = 4.31 \text{ mm}$ |
| $p_{ap0} = 0.85$ |
| $n_0 / z_2 = 17 / 2$ |
| $d_{ab} = 80 \text{ mm}$ |

**Process**

| Fly-cutting, climb cut, dry |
|---------------------------|
| $T = 8.1 \text{ mm}$ |
| $v_c = 150 \text{ m/min}$ |
| $f_a = 2.5 \text{ mm}$ |

**Fig. 3** Acceleration signals of the PM-HSS S390 fly-cutter in the time and frequency domain
are shown on the result figures on the left, Figs. 3 and 4. The material 42CrMo4 was machined with the HSS fly-cutter and the material EN-GJS-700-2 with the carbide fly-cutter. Both material/tool combinations lead to very fast progressive wear.

The feed rates were selected so that a maximum chip thickness according to Hoffmeister of \( h_{\text{max, Hoff}} = 0.2 \) mm occurred [20]. The cutting speed for the carbide tool was set to \( v_c = 300 \) m/min and for the HSS tool to \( v_c = 150 \) m/min. Milling with a fly-cutter was carried out until the tool broke or reached catastrophic wear. The aim was to detect breakage or wear of the tool in the sensor signals.

### 3.2 Analysis of signal data

#### 3.2.1 Trials with high speed steel S390

First, the results from the test series with the HSS fly-cutter are discussed. The cutting speed \( v_c = 150 \) m/min with a tip diameter \( d_{a0} = 80 \) mm resulted in a tool speed of \( n_0 = 9.94 \) s\(^{-1}\). For this test series, the sensor data of the tool-side acceleration sensor and the airborne sound sensor are presented, as the strongest effects were observed with these sensors. The results of the other sensors have not been listed for the sake of clarity. The signal data in the time (top) and frequency (bottom) domain are shown in Fig. 3.

A time interval of \( \Delta t = 5 \) s was considered. For the evaluation in the frequency domain, a Fast-Fourier-Transformation (FFT) of the signals was carried out in combination with a Hilbert transformation. The Hilbert transformation was necessary due to the signals high proportion of background noise. The signal amplitudes were not plotted against frequency, but against order, to ensure the comparability of the results also at different cutting speeds. The order is defined as frequency divided by the respective tool speed used.

The signal data from the machining of the first component were compared to the machining of the fourth. The difference in amplitudes was approx. 260%. The engagement impact of the tool with the workpiece can be clearly recognized in the worn fly-cutter by individual peaks in the time domain. In the frequency domain, peaks only occurred at integer orders. Higher amplitudes were measured in all orders after the occurrence of catastrophic wear.

#### 3.2.2 Trials with carbide K30

The test series with the carbide fly-cutter was terminated after the tool fractured during the machining of the third component. As the fracture only affected the signal data for a very small time increment, only the time domain was initially examined in more detail. An analysis in the frequency domain over the duration of the fracture was not possible due to the short time interval. Fig. 4 shows the signal data of the acceleration sensor on the tool-side and the airborne sound sensor at the time of the fracture occurrence. In addition, the active power of the spindle for the entire process is presented.

In the accelerometer data, a peak can be seen at the time of the fracture occurrence. After the breakage, the acceleration signal dropped to the background noise level because the fly-cutter was no longer engaging. In the signal of the airborne sound sensor, the breakage was not recognizable by a peak. Only the noise level dropped significantly after

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**Workpiece**
- Material: EN-GJS-700-2
- \( z_2 = 39 \)
- \( \beta_2 = 23^\circ \)
- \( b_2 = 30 \) mm
- \( d_{a2} = 116.2 \) mm
- \( d_{b2} = 100.0 \) mm

**Tool**
- Substrate: K30
- \( m_{n0} = 2.557 \) mm
- \( \sigma_{n0} = 17.5^\circ \)
- \( h_{ap0} = 4.31 \) mm
- \( \rho_{ap0} = 0.85 \)
- \( \eta_0 / z_0 = 16 / 1 \)
- \( d_{a0} = 80 \) mm

**Process**
- Fly-cutting, climb cut, dry
- \( T = 8.1 \) mm
- \( v_c = 300 \) m/min
- \( f_a = 4.7 \) mm

**Fig. 4** Signal analysis of tool breakage for carbide K30 fly-cutting trial
the failure. The same effect was observed for the effective power of the spindle. The failure was not detected by an increased peak in the effective power. Since the tool was no longer engaging after the breakage, the spindle power dropped to near zero.

Next, the signal data of the tool-side acoustic emission sensor with high frequency resolution of 100 MHz were analyzed in more detail. For the Qass sensor the analyzed time interval was reduced to $\Delta t = 0.064$ s. The continuous evaluation of the signal data with the Optimizer4D software allowed to evaluate the frequency even for short periods of time. Some irregularities in the form of peaks occurred in the signal data in the time domain. Fig. 5 shows such a peak. In the time-frequency analysis it can be seen that at the time of the peak especially the frequency $f = 64$ kHz was excited. In addition, the frequencies 45 kHz and 140 kHz were excited. The irregularities can be attributed to minor fractures on the tool cutting edge or formation of comb cracks. The later tool breakage could not be detected by the sensor. This may be due to the limited frequency domain considered. Frequencies below 50 kHz were not detected by the sensor. Since frequencies above 200 kHz were not excited, as can be seen in Fig. 5, a sensor with a lower frequency domain would probably be sufficient for the analysis of the hobbing process in the single tooth test and reduce the evaluation effort and data production.

Based on the analysis of the fly-cutting tests, it can be concluded that some sensors have potential for detecting breakage and wear during hobbing. Particularly clear results were achieved with both the tool-side acceleration sensor and the airborne sound sensor. The tool-side acoustic emission sensor can also be classified as suitable to a certain extent. The tool breakages could not be clearly identified with the acceleration sensor on the workpiece-side and the acoustic emission sensor. This can be attributed to the large distance between the mounting point and the cutting point and the resulting high attenuation.

4 Determining the sensor potentials during hobbing trials

In the course of the hobbing tests, the influences of the feed rate, the cutting speed and the wear condition of the tool on the sensor signals were examined. In addition, selected signals were investigated in a small series production. Finally, a conclusion is drawn regarding the suitability of using the sensors for tool condition monitoring in gear hobbing.

4.1 Analysis of the influence of the process conditions on the signal data

A PM-HSS hob with a normal module $m_{n0} = 2.5$ mm was used for the investigation of different process parameters. The detailed hob and workpiece geometry can be seen in Fig. 6 on the left. The tool was new without any wear. The trials were carried out without cutting fluid at three different feed rates of $f_a = 1$ mm, $f_a = 2$ mm and $f_a = 3$ mm with a cutting speed of $v_c = 200$ m/min. To analyse the influence of the cutting speed, it was varied from $v_c = 150$ m/min to

![Irregularity in the time domain](image1)

![Irregularity in the frequency domain](image2)

**Fig. 5** Analysis of the acoustic emission signals on the tool-side of the carbide fly-cutter
$v_c = 200 \text{ m/min}$ and $v_t = 250 \text{ m/min}$ by a constant feed rate of $f_a = 2 \text{ mm}$. The material 20MnCr5 was machined. Also one test point was carried out with a damaged tool.

In contrast to the fly-cutting tests, the evaluation of the signal data of the hobbing tests did not consider the raw data of the sensors, but characteristic values determined from the signal data. The maximum amplitude of the signal was analyzed, whereby larger peaks were declared as outliers and were not included in the evaluation. In detail, the acceleration $a_{\text{WST}}$ and $a_{\text{WZG}}$ on the workpiece and tool-side, the active power $P$, the airborne sound $SP$ and the acoustic emission $AE_{\text{rms,WST}}$ and $AE_{\text{raw,WZG}}$ on the workpiece and tool-side were considered in the time domain. Fig. 6 shows the influence of the feed rate on various sensor signals. The signals were examined in the time domain.

With an increase in the feed rate, the signal characteristics of the acceleration sensors and the airborne sound sensor increased as well. The same applies to the spindle power. For the acceleration sensors, the effect was stronger on the tool-side than on the workpiece-side. The opposite signal data were measured for the tool-side acoustic emission sensor. With an increase of the feed rate, the acoustic

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**Workpiece**

- **Material:** 20MnCr5
- $z_2 = 39$
- $\beta_2 = 23^\circ$
- $b_2 = 30 \text{ mm}$
- $d_{a2} = 116.2 \text{ mm}$
- $d_{i2} = 100.0 \text{ mm}$

**Tool**

- **Substrate:** PM14
- **Coating:** TiAlN
- $m_{n0} = 2.5 \text{ mm}$
- $a_{n0} = 20^\circ$
- $h_{ap0} = 3.45 \text{ mm}$
- $p_{ap0} = 0.5$
- $n_{i0} / z_0 = 13 / 1$, right
- $d_{a0} = 60 \text{ mm}$

**Process**

- Hobbing, climb cut, dry
- $T = 8.1 \text{ mm}$
- $v_c = 200 \text{ m/min}$

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**Fig. 6** Influence of the feed rate on the signal data

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**Workpiece**

- **Material:** 20MnCr5
- $z_2 = 39$
- $\beta_2 = 23^\circ$
- $b_2 = 30 \text{ mm}$
- $d_{a2} = 116.2 \text{ mm}$
- $d_{i2} = 100.0 \text{ mm}$

**Tool**

- **Substrate:** PM14
- **Coating:** TiAlN
- $m_{n0} = 2.5 \text{ mm}$
- $a_{n0} = 20^\circ$
- $h_{ap0} = 3.45 \text{ mm}$
- $p_{ap0} = 0.5$
- $n_{i0} / z_0 = 13 / 1$, right
- $d_{a0} = 60 \text{ mm}$

**Process**

- Hobbing, climb cut, dry
- $T = 8.1 \text{ mm}$
- $v_c = 200 \text{ m/min}$

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**Fig. 7** Influence of the cutting speed on the signal data
emission signal decreased. On the tool-side, the acoustic emission signal first decreased and then increased again. According to the state of the art, the AE amplitude, as well as the acceleration and the airborne sound, increase with increasing feed [3, 8]. This behavior was not observed in the results of the hobbing tests for acoustic emission.

The influence of the cutting speed on the sensor signals is shown in Fig. 7. For the accelerations, opposite curves were observed on the workpiece and on the tool-side. On the workpiece-side, there was a falling curve and on the tool-side an increasing one. The curve on the tool-side corresponds to the effect of increasing acceleration amplitudes with increasing cutting speed in the time domain, which is known from the state of the art [8]. On the workpiece-side an opposite curve was observed. Only the mean value of the effective power was influenced by the cutting speed. The mean value increased with increasing cutting speed. Increased values were also measured for the sound pressure with increased cutting speed. The acoustic emission sensors delivered different results. While there was no clear trend for the sensor on the workpiece-side, the signals for the sensor on the tool-side increased with the cutting speed. With increasing cutting speed, decreasing AE amplitude was found in previous investigations [3, 8]. This behavior was not observed in the acoustic emission signals.

Finally, the signals of the same process with two different tool wear conditions were compared. The two wear states are differentiated according to the tool in an undamaged state and with an average wear mark width of VB = 69 μm at the tip cutting edge, see the pictures in Fig. 8. The evaluation was carried out in the time and frequency domain.

For the acceleration sensors and the airborne sound sensor, similar effects were observed as in the fly-cutting tests. The amplitude of the signals in the time domain increased slightly with the worn hob. Due to the many overlapping tooth engagements, no clearly delineated peaks were recognizable in the time signal. Increased amplitudes at certain orders were also found for the signal data in the frequency domain. In contrast to the fly-cutting tests, the changes in the hobbing tests were better recognizable with the acceleration sensor on the workpiece-side. With the tool-side sensor, only a slight increase in amplitudes in the time domain could be detected. In the frequency domain, a broader frequency spectrum was excited by the damaged cutter. The tool-side acoustic emission sensor is examined in more detail in Fig. 8. In the time domain, the magnitudes of the amplitudes of the signal remained almost identical. In the frequency domain, two frequency sections were excited. The sections were delimited by the frequencies 37 to 96 kHz and 119 to 155 kHz, in each of which a clear peak occurred. In the domain 37 to 96 kHz, the peak before damage occurred at the frequency 80.07 kHz. After the damage, the peak shifted to the frequency 66.4 kHz with an approximately constant amplitude. In the frequency domain f = 119 kHz to f = 155 kHz, the maximum peak before damage was at the frequency of f = 125 kHz. After the damage, the peak was still at the same frequency, but on a larger amplitude.

According to the state of the art, the amplitude of the AE signal is significantly influenced by tool wear [8, 15]. A significant influence of wear was not found in the results of the time domain. A possible cause is the small wear in combination with the high background noise due to the position near the tool, which overlaps with the signal that reacts sensitively to the tool condition. Furthermore, according to Bhuiyan, the acoustic emission frequencies occur in the domain between 51 kHz and 620 kHz and vary

### Workpiece

**Material:** 20MnCr5

- $z_2 = 39$
- $\beta_2 = 23^\circ$
- $d_3 = 30$ mm
- $d_{a2} = 116.2$ mm
- $d_2 = 100.0$ mm

### Tool

**Substrate:** PM14

- $m_{r0} = 2.5$ mm
- $\alpha_{r0} = 20^\circ$
- $h_{aP0} = 3.45$ mm
- $\rho_{aP0} = 0.5$
- $n_0 / z_2 = 13 / 1$, right
- $d_{a0} = 60$ mm

### Process

Hobbing, climb cut, dry

- $T = 8.1$ mm
- $v_c = 200$ m/min
- $f_a = 2.0$ mm

![Fig. 8](image_url) Analysis of the signals of the acoustic emission sensor in the time and frequency domain
### 4.2 Analysis of signal data in small series production

In order to transfer the knowledge gained to the industrial environment, the internal production of test gears was examined using selected sensors. The choice fell on the acceleration sensors, which were mounted on the tool- and workpiece-sides. The trial setup can be seen in Fig. 9. A hob made of G50 with a module of $m_{n_0} = 1$ mm, a number of gashes of $n_{i_0} = 14$ and a number of starts $z_0 = 1$ was used for the small series production. The batch comprised 90 gears made of 16MnCr5. The workpiece had a number of teeth of $z_2 = 102$ and a helix angle of $\beta_2 = 0^\circ$. The workpiece width was $b_2 = 20$ mm. Cyclic shifting was selected as the shift strategy. The strategy is shown in the sketch of Fig. 9. Shifting is the process of moving the cutter tangentially to the workpiece by each part to different machining points so that the cutter wears evenly over its entire length. With each pass the shift positions are shifted a bit to each other.

Fig. 10 shows the maximum spindle power and the acceleration on the tool- and workpiece-side over the number of machined workpieces, as well as the condition of the cutter before and after machining. At the end of machining, the cutter showed an average wear mark width at the tip of $VB = 40 \mu$m. The spindle power showed a slight increase over time. It is known from the state of the art that the spindle power increases with increasing wear [21]. This observation was confirmed despite the very low wear on the tool.

On the right of Fig. 10, the maximum acceleration on the workpiece- and tool-side is plotted over the machined workpieces. The influence of wear is barely visible in the acceleration data on the tool-side and not visible in the signal for the workpiece-side. It is noticeable that the spindle power signal and the acceleration on the tool-side are subject to relatively strong fluctuations despite a positive increasing trend. For the spindle power, an approximately periodic variation with constant wavelength was observed. The wavelength corresponds to a shift cycle. The shift position of the cutter therefore has a strong influence on the measured spindle power.

The fluctuations of the acceleration values are examined in more detail in Fig. 11. The time domain is shown on the left and the frequency domain for three different highly excited orders are shown on the right. In addition, the shift cycles of the tool were marked in the diagrams. The shift increment was $S = 3.142$ mm. For the orders considered on the tool-side, the shift position showed no influence on the signal response. Also, no clear correlation between the shift position and the sensor signals could be detected in the time domain. For the orders considered separately for each workpiece, each shift cycle showed the same acceleration curve. The maximum acceleration for the 14th and 154th order was at the end of the shift cycle and for the 84th order at the beginning of the shift cycle. No more fluctuations in the acceleration values could be detected in the time domain. The individual frequencies therefore cancel each other out due to the superposition.
Another challenge with TCM is the filtering of the signals with regard to environmental influences that irregularly overlay the signal. The band-pass filter used in these investigations was partly insufficient to completely filter external vibrations originating outside the machine tool. Insufficient filtering distorts the evaluation of the signal data.

5 Summary and outlook

In this report, the potential of different sensors for tool condition monitoring in gear hobbing was analyzed. Based on the fly-cutting trials, statements were derived about the suitability of the sensors with regard to tool breakage detection. Particularly good results were obtained with the tool-side acceleration sensor and the airborne sound sensor. With the sensors mounted on the workpiece-side, the tool breakage could not be detected. The tool-side acoustic emission sensor proved to be suitable to a limited extent. For further investigations, an acoustic emission sensor with a lower frequency domain should be used, since the strongly excited frequencies were below 200 kHz.

During the hobbing trials, the suitability of the sensors with regard to the detection of wear as well as the influence of the process parameters on the signals could be determined. The influence of the process parameters was best

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**Workpiece**

Material: 16MnCr5

- \( z_2 = 102 \)
- \( \beta_2 = 0^\circ \)
- \( b_2 = 20 \text{ mm} \)
- \( d_{a2} = 101.5 \text{ mm} \)
- \( d_{d2} = 98.1 \text{ mm} \)

**Tool**

Substrate: G50

- \( m_{n0} = 1 \text{ mm} \)
- \( \alpha_{n0} = 20^\circ \)
- \( h_{ap0} = 1.4 \text{ mm} \)
- \( p_{ap0} = 0.39 \)
- \( n_{0}/z_0 = 14/1, \text{ right} \)
- \( d_{ao} = 60 \text{ mm} \)

**Process**

Hobbing, climb cut, dry

- \( T = 1.35 \text{ mm} \)
- \( v_c = 200 \text{ m/min} \)
- \( f_a = 1 \text{ mm} \)
detected by the acceleration and acoustic emission sensor on the tool-side and the airborne sound sensor were found to be of limited suitability. For wear detection, the workpiece-side acceleration sensor, as well as the airborne sound sensor showed the best results. The tool-side acceleration sensor and the power sensor were also rated as conditionally suitable. With the tool-side acoustic emission sensor, slight changes due to wear were only detected in the frequency domain.

For a good assessment of the tool condition depending on all influencing variables, the use of a combination of different sensors is recommended. In addition to the process parameters, variables such as workpiece material, shift position and external influencing factors (other machines, machine operator ...) also have an influence on the signal response. For an accurate analysis, the cutting conditions of the individual cuts should also be included, which could be determined by means of a penetration calculation.

For a more meaningful analysis of the sensor potentials, further tests with a larger test scope are necessary. For this purpose, further tests in single tooth engagement (fly-cutting) as well as hobbing tests must be carried out, in which the sensor signals are analysed taking into account the knowledge gained from this work and the influence of progressive wear is determined.

**Code availability** Not applicable

**Availability of data and material** Not applicable

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