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Process-parallel center deviation measurement of a BTA deep-hole drilling tool

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Abstract

The BTA deep-hole drilling process is used to manufacture holes with a high length-to-diameter ratio of up to 100. A major quality criteria is the difference between the drilled hole axis and the desired, ideal straight hole axis, called center deviation. A novel measuring system is being investigated in order to measure the center deviation simultaneously to the drilling process. The deviation is determined by calculating the bending line of the boring bar using a newly developed algorithm. The measuring system consists of four subsystems: Optical fiber Bragg grating (FBG) sensors, four eddy current sensors, a rotary encoder and a displacement encoder. These subsystems enable a spatial measurement visualization of the bending line and the center deviation at the head of the boring bar. A major challenge is the separation of the bending strain from other undesired strain fractions. This is done by using an arrangement of two FBG sensors and a digital band pass filter. Experimental investigations show sufficiently good agreement between the calculated and the actual center deviation. Furthermore, drilling experiments reveal that the measurement setup can be used for additional process monitoring by using frequency analysis. Therefore, the investigated system is able to visualize and observe the center deviation. The visualization can be used to derive adequate countermeasures in order to ensure a better process control for the machine operator. The objective of the investigation is to increase the process reliability and productivity by preventing scrap parts. Within this paper, the investigated measuring system, the calculation of the center deviation and first experimental results are described.

Keywords: deep-hole drilling; center deviation; fiber Bragg grating

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1. Introduction

In some areas of the oil- and aircraft industry, holes with a high length to diameter ratio (l/D-ratio) are needed. The BTA (Boring and Trepanning Association) deep-hole machining principle is usually applied for diameters between 16 and 1,000 mm and l/D-ratios of up to 100 [1]. The BTA principle is characterized by a boring bar and a coolant oil supply around the outside of the cutting tool between boring bar and the holes inner wall. The chips are carried out of the drilling hole using the coolant oil flow as a transport medium. The deep-hole drilling process is often used within the last steps of a process chain. This leads to high reject costs in case of quality defects during the BTA process. A high process reliability is therefore necessary. A major quality criteria is the geometric difference between the drilled hole axis and the desired, ideal straight hole axis. This difference is called center deviation *m* (Fig. 1). Due to the high l/D-ratio, the stiffness of the boring bar is low. This enhances the emergence of a center deviation during a deep-hole drilling process. Depending on the drilling diameter and utilized drilling tool, the center deviation *m* can achieve values of up to 0.5 mm per meter drilling depth.

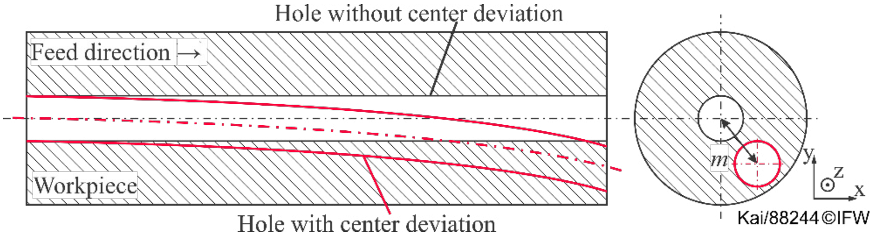

Fig. 1. Illustration of the center deviation of the boring bar

One approach to measure the center deviation is to measure the wall thickness from the outside of the workpiece with an ultrasonic system [2]. In [2], a mechanical pressure device is used to redirect the boring bar in order to reduce the center deviation. The disadvantage is the ultrasonic systems susceptibility towards the rough environment. The system is also usually used for drilling eccentric drill holes with a stationary workpiece. Katsuki et al. use a laser guided deep-hole boring tool with integrated piezo-actors. Four position-sensitive diodes are utilized to measure the center deviation during the process. However, this system can only be used for reducing the center deviation during drill-out operations. Consequently, this system is unsuitable for full drilling operations [3]. Other systems [4] are based on alignment telescopes or autocollimators. However, with these measuring systems, an interruption of the process is necessary [4]. Therefore, a novel measuring system is being investigated in order to measure the center deviation simultaneously to the drilling process. The deviation is determined by calculating the spatial bending line of the boring bar with a newly developed algorithm. This algorithm is primary based on measured strains using optical FBG sensors. Therefore, two arrays with up to 18 different measurement points in each fiber is used to measure the strain at the boring bar surface. The FBG sensor technology is already being used for civil engineering or medical applications. The sensors are used for spatial shape remodeling within structural frameworks [5] or colonoscopes [6]. Frenet functions are used to describe the necessary space curves of a colonoscope as a function of the colonoscopes length [5]. The boring bar has a very small curvature in comparison to the bar length, so using frenet functions is not reasonable [7]. The herein described calculation is therefore based on Cartesian equations. The investigated system to measure the center deviation is based on a bending line calculation by measuring the bending strain distribution with FBG sensors. The system can be used simultaneously to the drilling process. The next chapter gives an introduction in the investigated measuring system to fulfil the objective of measuring the center deviation.

Nomenclature

A	Normalized amplitude
BTA	Boring and Trepanning Association
e	Bending line calculation error
ε	Measured bending strain
f	Frequency

FBG	Fiber Bragg grating
m	Center deviation
r	Boring bar radius
s	Deviation at the boring bar head
y	Deviation of the boring bar
z	Boring bar length

2. Introduction to the Measuring System

The newly developed measuring system for the determination of the center deviation is shown in figure 2 within a schematic drawing of a BTA deep-hole drilling machine. The drilling machines have usually two spindles to drive the boring bar, the workpiece or both counteractive. The workpiece is clamped between the workpiece spindle and the oil pressure head. The boring oil is supplied through the oil pressure head into the annulus between boring bar and manufactured drill hole in order to reach the drill head. At the drill head are the cutting edges and the guide pads located. These pads guide the boring bar inside the manufactured hole. Between the oil pressure head and the tool spindle is the damper located, that damps the torsional vibrations.

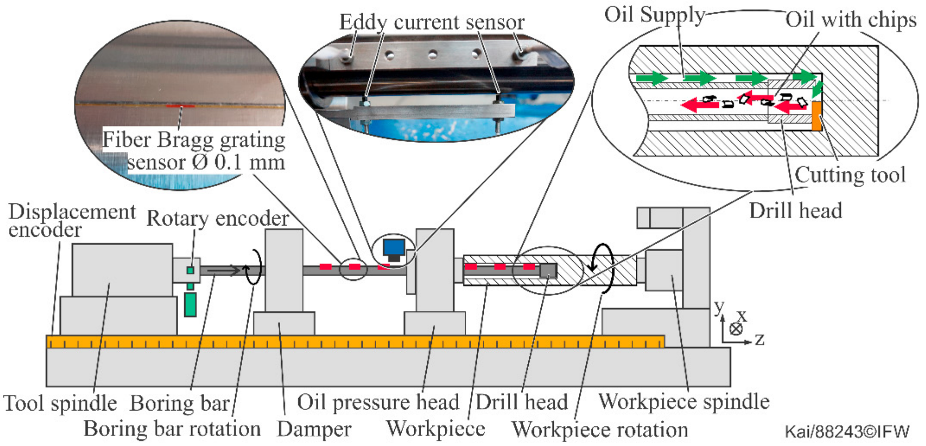

Fig. 2. Schematic deep-hole drilling machine with measuring system

The investigated measurement system consists of four subsystems. These subsystems are described in figure 3 with the determined value and the function of the data within the algorithm. Two FBG sensors are applied within two flutes along the boring bar. The flutes are located on the outer lateral surface of the boring bar with an angular offset of 180 degree. The FBG sensors are used to measure the strain at ten equally distributed positions along the boring bar front. The FBG sensor is an optical measurement device. A broad light spectrum is sent into a glass fiber with a diameter of 0.1 mm. Each FBG reflects a defined wavelength that shifts in consequence of varying strain or temperature. All other wavelength of the spectrum are transmitted. Thus, it is possible to measure the strain at different positions within only one glass fiber, called multiplexing. The 180-degree arrangement of the two FBG sensors is also chosen for the compensation of the statically strain fractions by subtracting the signals from each other. The measured signals are used to determine the strain distribution along the boring bar between the drill head and oil pressure head. This strain distribution is used to calculate a two-dimensional boring bar bending line in the first instance. The calculation is described in section 3. Four eddy current sensors are used to determine the tilting angle of the boring bar and its horizontal and vertical displacement relative to the oil pressure head. Two eddy current sensor pairs are located in a 90-degree angle to each other. Moreover, each sensor pair has a different distance in z-direction to the oil pressure head, like shown in Fig. 2. Consequently, it is possible to calculate the displacement and the tilting angle of the boring bar in x and y-direction. These values are used within the bending line algorithm as mechanical boundary conditions. Therefore, the bending line equation is solvable (see chapter 3) and a reference between oil pressure head and boring bar is established. The rotary encoder is used to measure the boring bar angular position, respectively the angular position of the FBG sensors and the actual rotational frequency. The signals are used for calculating the bending line as a function of the rotational state of the boring bar. This additional signal input allows the calculation of a spatial bending line. The signal of the displacement encoder is additionally used to determine the measurement points located inside the drilled hole. These points are relevant to calculate the bending line between the oil pressure head and drill head. This algorithm is described within the following chapter 3.

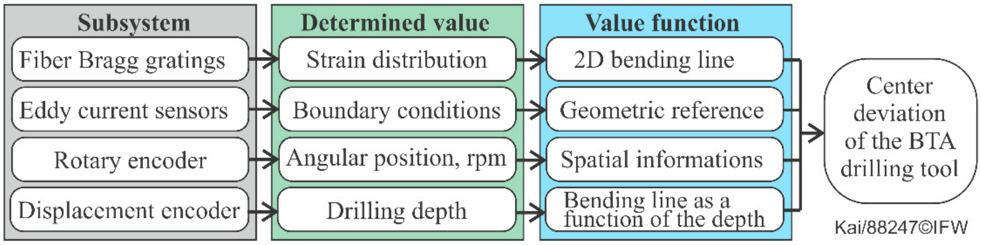

Fig. 3. The four sensor subsystems

3. Calculation of the center deviation

The actual center deviation is the maximum value of the spatial bending line function at the drill head. With the FBG sensors, the total strain at the surface of the boring bar is determined. However, for the calculation of the bending line, only bending strains are relevant. Hence, it is necessary to separate the bending strain from other strain fractions such as temperature, feed force and torsion. Only the bending strain circulates with the boring bar at the rotational frequency. A Butterworth band pass filter is therefore applied to separate the desired bending strain at the rotational frequency. To achieve this separation, the signals of all frequencies except the rotational frequency are removed. For this reason, the signal of the rotary encoder is used to evaluate the actual rotational speed. The calculation is done discontinuously, by buffering all measured data for a defined number of revolutions. The algorithm is then applied to the buffered data. Thus, the calculation and visualization of the center deviation within the graphical user interface is done every five seconds. This update frequency is adequate as the BTA boring processes usually take up to 30 minutes depending on the drilling depth and diameter. In this exemplary process, the center deviation is calculated and visualized 360 times. This leads to accurate measurement and a high process knowledge. After separating the bending strain from the statically strain fractions, the actual bending line algorithm occurs. Firstly, the information about the drilling depth, provided by the displacement encoder, is used to determine the number of relevant measurement points between the drill head and the eddy current sensors. A spline approximation is used to generate a continuous strain function between all relevant measurement points. The actual bending line calculation is done based on the Bernoulli bending beam model. Thus, the displacement $y(z)$ can be described as the double integral (eq. 1) of the strain distribution $\varepsilon(z)$ [8]

$$\mathrm{m(z)}=\frac{1}{\mathrm{r}} \iint_0^{\mathrm{z}} \varepsilon(\mathrm{z})\ \mathrm{dz}^2 \ . \qquad \text{(eq. 1)}$$

The solution of this double integral leads to the emergence of two unknown variables. In the case of a bending line as the mechanical boundary conditions displacement and tilt angle. The necessary boundary conditions are provided by the signals from the four eddy current sensors, respectively the displacement and tilting angle at the beginning of the bending line. The next chapter 4 describes the experimental test results to verify the bending line algorithm and the determined boundary conditions.

4. Experimental test results

In order to verify the previously described algorithm, experimental tests has been done. Figure 4 shows the applied test setup using a boring bar with a length of 1,400 mm, an outer diameter of 42.2 mm and an inner diameter of 37.4 mm. At the beginning of the boring bar, a rigid clamping mechanism is located and at a distance of 600 mm an additional bearing. With these two bearings, the test setup is statically indeterminate. However, the described calculation approach is independent from the static determination. The strain distribution already contains this mechanical information. The strain measurement points are marked as blue bars. The laser sensor is used to measure the absolute deviation *s* at the top - marked purple. The chart illustrates the calculated deviation *m* depending on the measured deviation *s*, shown as rectangular markers. The diagonal line shows the ideal correlation between these two values. The first experimental investigations under static conditions show a good correlation between the calculated and the actual, measured center deviation. The accuracy is sufficient to calculate the center deviation of the drilling process with the expected deviation of up to 0.5 mm per meter drilling depth. The maximum bending line calculation error at the head of the boring bar is 8 µm at a maximum measured deviation of 0.34 mm. Inaccuracies arise on the one hand because of non-ideal test setup conditions. On the other hand is the algorithm not able to describe discontinuities in the strain distribution like at the bearing position. This leads to additional inaccuracies.

Additional, drilling experiments were completed to verify the test setup with the eddy current sensors. In this test, a hole with a depth of 1,400 mm a diameter of 50 mm was drilled with the deep-hole drilling machine. The determined deflection is 9 µm and the resulting tilt angle is 0.003 °. Nevertheless, even small tilting angles at the beginning of the boring bar can cause high center deviations at the drill head, as the boring bar length is high.

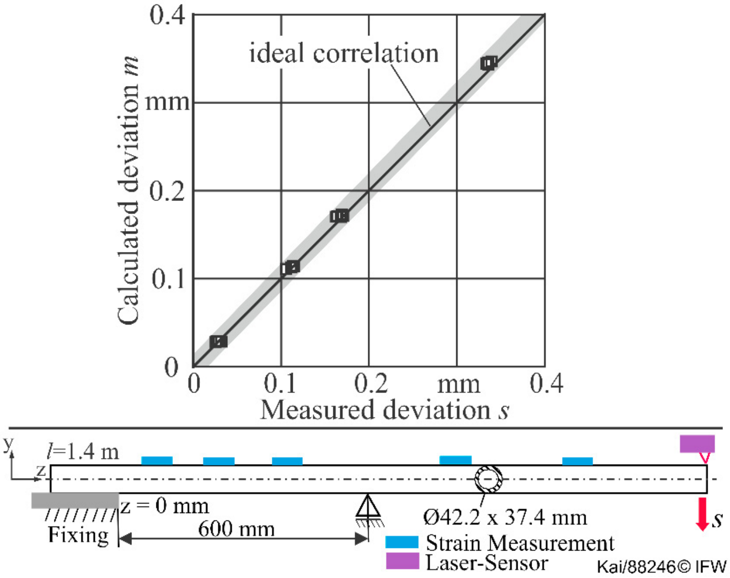

Fig. 4. Center deviation calculation error

An advantage of the FBG sensor approach is the possibility to apply the measurement points near the process. Therefore, the sensitivity of the strain measurement for significant process values is high. Furthermore, an additional process monitoring is possible, like a frequency process analysis. In Figure 5, a normalized resilience frequency response during a drilling process is illustrated. It was recorded using one FBG sensor located behind the oil pressure head. The rotational frequency *f* of the boring bar is 4.9 Hz (294 revolutions per minute). The amplitude *A* at the rotational frequency sets out the desired bending strain, as described in chapter 3. The blue marked area at 4.8 to 5.0 Hz illustrates the passing frequency for filtering with the band pass filter. The normalized bending strain amplitude is 0.085 and small in comparison to the static strains. This shows that the bending strain represents only a small portion of the overall strain at the boring bars surface.

Besides the rotational frequency, other frequencies are noticeable. The peaks at low frequencies up to 50 Hz are multiples of the rotational frequency. The quadruple at 19.6 Hz is especially high compared to the other multiples. This can be attributed to the outer cutting edge and the three following guide pads that are equally distributed along the circumference. Another noticeable frequency is located at 385 Hz. This is a torsional frequency typically occurring during BTA deep-hole drilling processes. The dynamic effects were also investigated in other studies about frequencies within deep-hole drilling processes [9, 10].

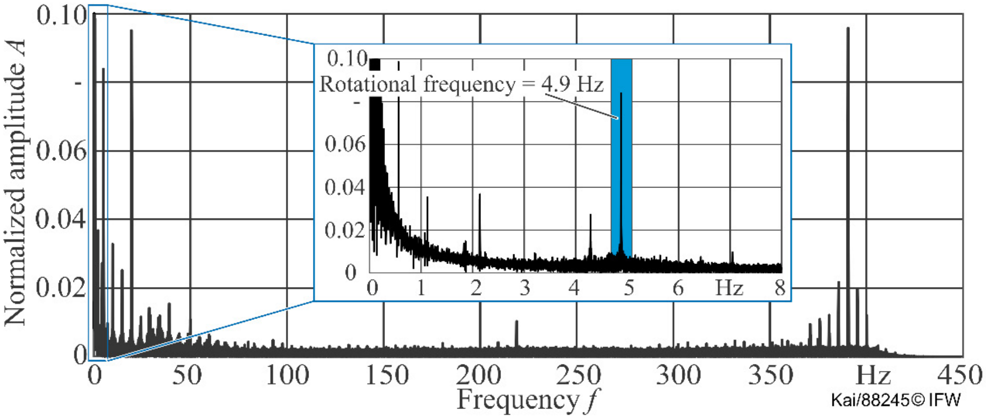

Fig. 5. Normalized resilience frequency response during a BTA drilling process

5. Conclusion and Outlook

The center deviation is a major quality criterion of the BTA deep-hole drilling process. A measurement system was investigated for observing and visualizing the center deviation during the deep-hole drilling process. This leads to a higher process knowledge for the machine operator. The information can be used to achieve a higher process reliability and productivity by preventing scrap parts. The measuring system consists of four subsystems: Two fiber Bragg grating sensors, four eddy current sensors, a rotary encoder and a displacement encoder. All signals are used to calculate a spatial bending line of the boring bar. The center deviation is derived from this bending line. First results under static conditions reveal a sufficient measurement accuracy of the introduced system. Consequently, it is suitable to calculate the bending line of a boring bar during a BTA deep-hole drilling process. This is a fundamental step towards an automated center deviation compensation. Therefore, a closed loop system with existing compensation methods can be designed. Additionally, the results of the frequency analysis reveal that it is possible to monitor other process characteristics. Further experimental tests are planned to evaluate the ability of the overall system for the determination of the spatial bending line, the center deviation and the technical limit of the approach.

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