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RELATION OF PROCESS AND CONDITION MONITORING AT DEEP HOLE DRILLING

Process monitoring and condition monitoring are closely related. The basic structure of the tasks is the same. In some cases the may even use the same set of raw data. Monitoring of a process is also influenced by the machine's state. Therefore, the state has to be monitored also. In most cases wear causes a divergence of the intended from the actual state. The paper presents the principles of monitoring the condition of a main spindle as well as monitoring the process of deep hole drilling.

1. INTRODUCTION

Process and / or condition monitoring consists of several functionalities and tasks that form its structure. They can be separated into data acquisition description of the monitored system separation of relevant data and analysis. Fig. 1 illustrates the principal structure with its inputs, functionalities and output. Usually, the data will be processed by a quality management department.

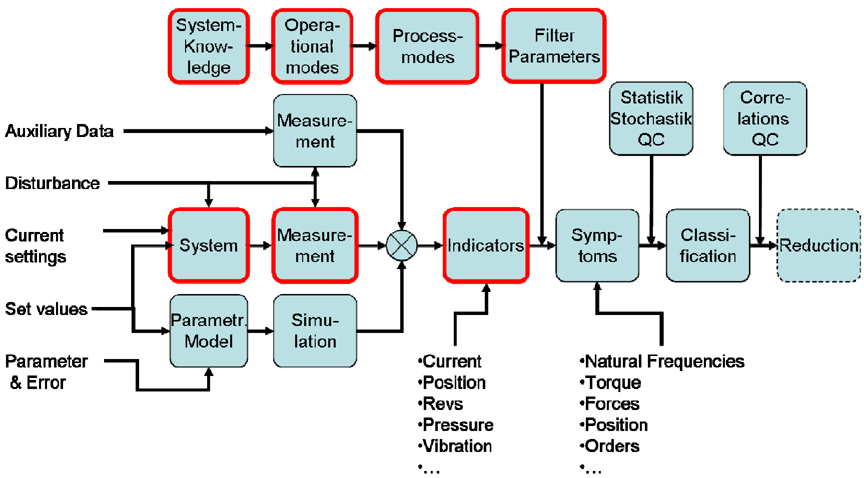

Fig. 1. Structure of process monitoring

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During the data acquisition the monitored system’s state is determined by current settings set values disturbances environment and so on. The task is to separate the relevant data. Simplest approach is to acquire data during the system’s operation either by sensors or by reading the controller data. In Fig. 1 the least necessary tasks for monitoring are marked red. In this case only data are acquired and analysed. No parametrical model is used so far. For analysing the data the relevant modes have to be separated. Mode separation is based on system knowledge. System knowledge usually is presented as a model. On basis of this model operational modes are identified. Within these the process-relevant ones have to be separated. The means for that is filtering time based data. To parameterize the filter the system i.e. process is analysed. The filter separates the symptoms from the indicators. A real system is contained in its environment. Therefore, the environmental data has to be captured also. The method is completed by modelling the systems operation and comparing it to the measured data. The purpose of the established system is determined by the kind of modes that are filtered. That means the basic structure will be the same for condition or process monitoring respectively. The main difference will be the kind of filtering and the filters’ settings.

2. CONDITION MONITORING OF MAIN SPINDLES

At the Institut fuer Werkzeugmaschinen (IfW) of the Universitaet Stuttgart wear of main spindles is detected. Main spindles contribute a lot to the availability of machine tools (Fig. 2) [1].

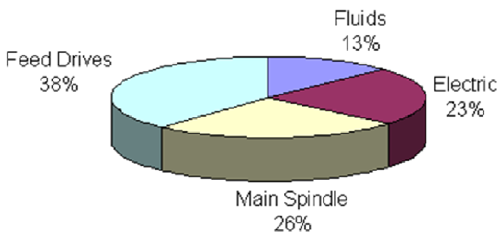

Fig. 2. Ratio of failure causes at machine tools [1]

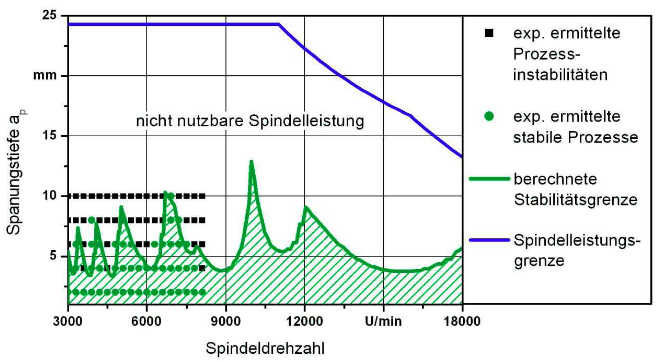

Fig. 3. Limitations of the usability of the main spindle's performance due to dynamic stiffness [2]

Main spindles are a key factor to the performance of machine tools. The performance of the machine also is determined by its dynamic behaviour [2] and the state of its drives [3]. Fig. 3 shows the usable range (green) of a spindle's performance that is determined by the machine's dynamic stiffness. It can be seen that the spindle's performance may not be fully exploited. On the other hand it is the spindle's performance itself that limits the total performance.

3. KNOWN PROCEEDINGS FOR CONDITION MONITORING OF MAIN SPINDLES

In most cases main spindles are regarded as electric motors containing two bearings and the rotating spindle. That's why the principles of bearing condition monitoring were adopted to main spindles. State of the art is to place a vibration sensor in close vicinity to the spindle's bearings and to analyze the vibration data. Fig. 4 exemplarily shows the installation of a vibration sensor. The acquired signal is an amplitude modulation of the surrounding parts' natural frequencies excited by the bearing's characteristic frequencies [4]. The signal processing has to be done by demodulation.

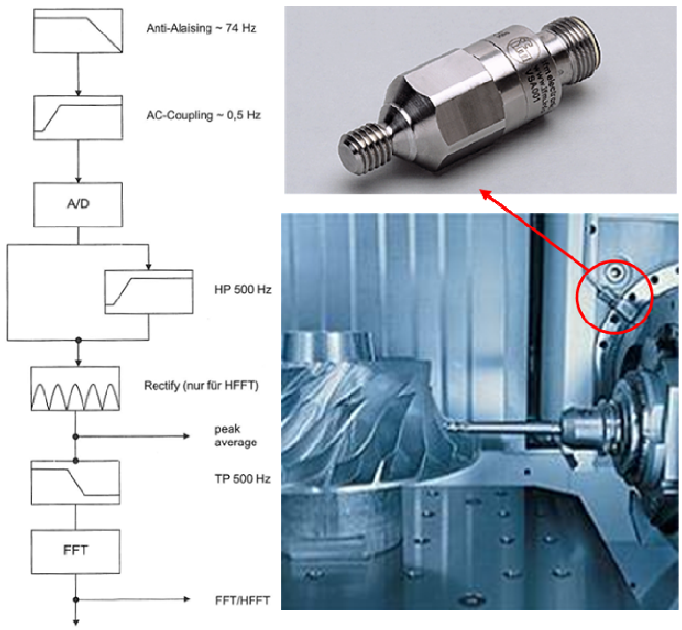

Fig. 4 Scheme for demodulating vibration data for bearing condition monitoring (left). Condition monitoring with a capacitive acceleration sensor (right)

Fig. 4 shows the typical demodulation for bearing conditioning sensors. This approach can often be found on main spindles. For its realisation specific sensors are necessary. In most cases only one sensor is applied. Using only one sensor means that the data have to be treated as an absolute value. That means transmission behaviour between different sensor locations or a relation of different physical dimensions is not possible. Monitoring the condition of a main spindle’s bearings may be only one measure. Main spindles may not be treated as simple electric motors. Among others, the requirements for a main spindle are:

- Geometrical fixture of the tool.
- Transmission of the driving power.
- Good behaviour of its accuracy.
- High static and dynamic stiffness.
- High balancing quality.
- Thermal stability.
- Low axial and radial bearing play.
- Low radial run-out tolerances.

Condition monitoring with means of roller bearing monitoring may not cover these requirements. Fig. 5 shows the bearings that are used in main spindles according [5].

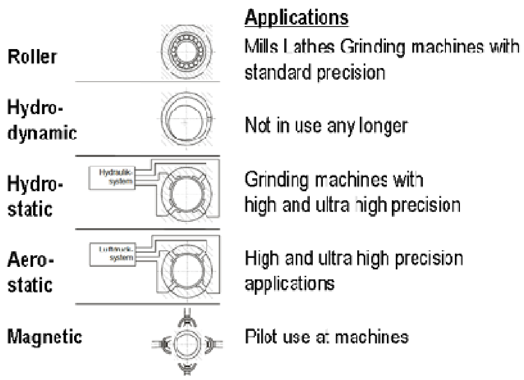

Fig. 5 Bearings of main spindles an their application

At the IfW a different method is used. It is based on a sensor that already is installed in the machine. The intended application of the Blum Novotest “LaserControl“ among others is to determine a tool’s length and diameter for TCP compensation in the machine’s CNC control unit as well as for detecting breakage. One principal advantage of the sensor is that it can operate in rough environments (Fig. 6, left).

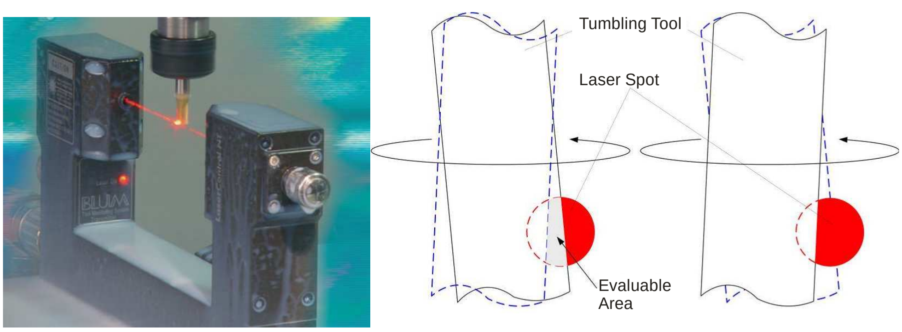

Fig. 6. Sensor Blum Novotest “LaserControl“ for detecting tool

The sensor is designed to put out a binominal value when the laser is beam is touched or not. The geometrics of the tool are determined by using this signal as a trigger for the current positional data of the machines axes. A closer look to this principle reveals further applications. Since the laser beam has a finite thickness i.e. it is not zero switching its output is a transient process. The sensor's hardware includes a Schmitt-Trigger that sets the output. When certain coverage of the beam is reached the output is triggered. The state between touching and full coverage generates an analogous signal that is proportional to the axes displacement. When the axes are resting the signal is caused by the tool's motion in the spindle (Fig. 6, right). The "LaserControl" is offered in different versions. Here the spot's maximal diameter is 30 µm. At average sized milling machines a main spindle's acceptable concentricity error is 2.5 µm to 5 µm. For grinding machines it is 0.1 µm to 0.5 µm. The tolerated axial error is 0.1 µm to 1.5 µm. Therefore, the range of the sensor i.e. its laser's focussed spot diameter is sufficient. It has to be investigated whether the resolution is high enough. For investigating the sensor's capabilities it was compared to a laser vibrometer while measuring the vibrations of a beam (Fig. 7).

Fig. 7. Comparing the Blum Novotest LaserControl to a laser vibrometer

The data were acquired with a frontend for dynamic measurements. Before, both systems were calibrated (Fig. 7, right). For the measurements the beam was excited with a blow of a hammer. The vibrometer and the sensor were sampled simultaneously with the same settings. Fig. 8 shows the compliance of the data in time (above) and frequency domain. The length of the beam was altered as was the excitation. The data proved to stay compliant.

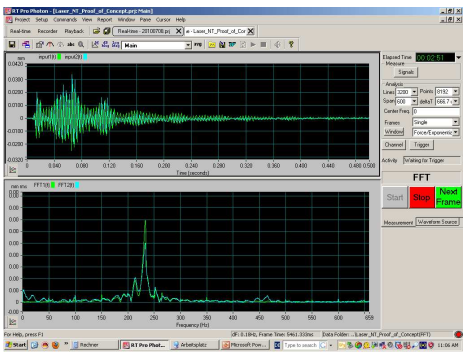

Fig. 8. Compliance of laser vibrometer (green) and LaserControl (blue)

In order to predict the necessary frequency range the frequency response of a spindle was measured. The acceleration sensor was placed at the spindle's casing similar to Fig. 4 and at the tool, where the "LaserControl" will measure. The results are shown in Fig. 9.

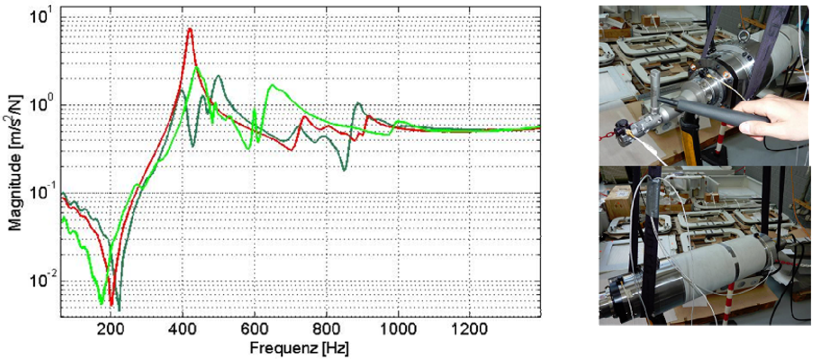

Fig. 9. Frequency response of a main spindle at the casing (green) and at the tool (red)

The sensor is capable to cover the relevant frequency range. Further test have shown that the frequency range of the sensor by far exceeds the needs of the necessary dynamic measurements. Since the "LaserControl" sensor acquires static and dynamic displacement it can directly measure some of the spindle's capabilities. The sensor or the tool respectively can be placed to measure axial displacement also.

Bearing diagnosis is based on a stationary state during data acquisition. Therefore, the spindle is run at constant speed. Empirical knowledge is that things break under changing load i.e. transient state. The load has to be similar to the one which is implied during operation of the machine. For that an adjustable imbalance is designed to specifically excite the spindle's relevant frequencies. The exciter is designed to be stored in the tool surveyor (Fig. 10).

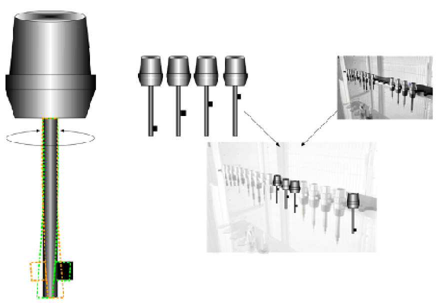

Fig. 10. Adjustable exciter for specific load of main spindle

The method directly evaluates the spindle's geometric behaviour during steady and transient states. The presented method is based on dynamic balancing as well as on static displacement it directly asses the shaft's behaviour. By using the machine's data such as position and rpm several physical dimensions are used. By placing the axes i.e. the sensor at different relative positions transmission paths may be investigated. Modern main spindles feature different kinds of bearings. Especially for high precision applications hydrostatic fluid bearings are used. Thermal warpage is likely to take place. Another aspect is permanently remaining static deformation of the shaft. These aspects may not be covered by classical bearing diagnosis. The presented concept directly measures the spindle shaft’s axial and radial displacement. The spindle’s casing is not included in the transmission path. A complicated error prone demodulation according Fig 4 is not necessary. In many cases wear of bearings is a secondary effect caused by geometrical deformations that may not be detected with vibration based bearing diagnosis. Axial displacements also may not be detected. Since the measurements are performed under a certain known load the dynamic behaviour of the machine’s structure also is included into the data. Therefore, further specific measurements are not needed.

Classical methods are bound to static states. Also noise affects the measurements. That’s why they are performed while the spindle runs in idle. The component that has to be monitored is the spindle shaft. Since system reacts much more sensitive to transient excitation an adjustable supplementary load has to be implied during measurement. Running the spindle in idle will not excite the relevant operational modes. The supplementary excitation has to be similar to the process that runs on the machine. Often, as the following description of deep hole drilling shows a process is not stable. Mainly transient states determine a process’ or system’s limits.

4. PROCESS OF DEEP HOLE DRILLING

Nowadays drilling operations play an important role in cutting processes. This increasingly requires drill holes with a length that is many times higher than the diameter. These demands led to the development of special deep hole drilling processes, each of which can cover a certain diameter range. The application possibilities here range from tunnel drilling or drillings for oil production with hole diameters in the range of several metres to the application for smallest diameters in the millimetre range, for instance, in the case of fuel channels in common rail diesel injectors. The present paper deals exclusively with the latter problem and the specific characteristics resulting from this.

As a rule, gun drilling methods are used for deep hole drilling with smallest diameters, for example, in the range from d = 1 mm to d = 2.5 mm. As these are often mass productions or contract works, these deep hole drillings are especially aimed at achieving short cycle times coupled with smallest possible downtimes by minimised production rejects. Hence production processes are often operated bordering on the limits of their stability, which counteracts the demand for process stability in the form of little downtimes.

This is the reason why the current developments in gun drilling with smallest diameters are primarily concerned with the question of a process monitoring strategy by which it is possible to detect errors in the process in the best possible time and take appropriate measures with the greatest possible degree of automation as well.

Gun drilling processes are susceptible to failure as regards many process influence factors, not least due to the slim tool geometry. In the following, the fundamental effects arising are given, and it is explained which of them lead to process disturbances in gun drilling.

5. CHIP CLOGGING / ENTANGLEMENT

Apart from the above-mentioned process disturbances, arising in many drilling processes, there are specific phenomena for gun drilling. These effects are chip clogging and chip entanglement, which result from the special chip removal process and arise depending on forming chips as well as on the dynamic pressure of the coolant at the drilling head. To illustrate the problem, Fig. 11, left shows the removal of the typical chip in a stable and stationary process stage.

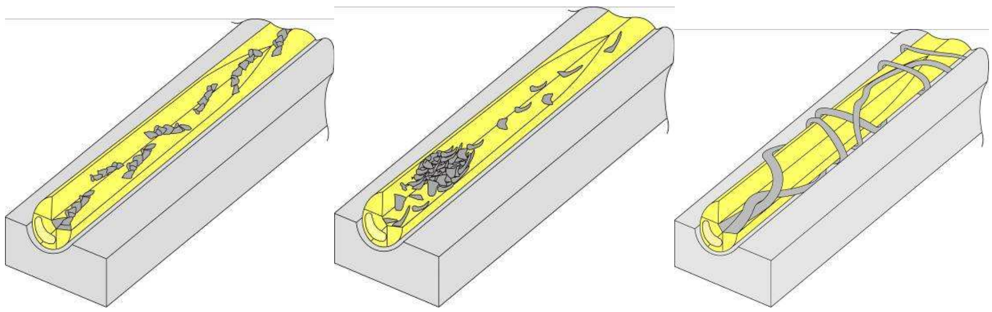

Fig. 11. Chip removal in stationary process, processes disturbance of chip entanglement and clogging (left to right)

If the coolant pressure at the drilling head or the length of the forming chip decreases here, there is a danger of a so-called chip entanglement, also often called chip crowding in literature.

In accordance with Fig. 11, centre, bulky chips are formed here, which crush each other in the chip flute and can often not even be removed out of the shank flute through drastically increasing the coolant pressure. This leads not only to a corresponding decrease in the surface quality of the drill hole due to the abrasive effect of the chips on the drill wall but also to a considerable destabilisation of the drilling process. One the one hand, the dynamic forces at the drilling head greatly increase due to the decreasing coolant flow in the chip flute, by which the chip formation may be influenced negatively in turn. On the other hand, the changed loads may cause torsional and flexural vibrations especially at the drill shank, which may relatively quickly result in a breakage of the shaft relatively fast [6],[7].

6. CHIP CLOGGING

Apart from too short chips, primarily too long chips impair the process stability in gun drilling, see also Fig. 11, right.

Particularly due to unfavourable machining conditions, long, ductile chips may form, wrapping themselves around the shank and thus leading to a clogging of the chips between drill wall and drill shank. This often results relatively quickly in a breakage of the drill.

At the beginning of the chip clogging, a great fluctuation in the drilling moment arises because of settlement processes and subsequent removal processes of the chip. With growing chip clogging, the resultant forces increase very much until the load limit of the drill shank is exceeded and the shank of the gun drill usually breaks [8]. In addition, chip cloggings forming outside the drill hole may also lead to a breakage of the drill. Snarled and ribbon chips are formed here wrapping themselves around the shank and gradually preventing the chip-coolant mixture from coming out of the drill hole again. But this in itself becomes critical for the process only when a tailback is caused by that, in turn leading to a chip crowding inside the drill hole [8].

Whereas it is usually possible to continue the process if the disturbances mentioned are detected in time and suitable measures are taken, it is impossible to continue deep hole drilling if the tool shank has a crack. This is usually caused by an overload of the drill shaft due to high torsional and bending loads, which is why the tool part from the point of break to the cutting edge gets stuck in the drill hole made already and can often not be removed again. Hence a tool breakage causes not only downtimes of the machine due to the necessary tool change but also the fact that the workpiece machined before is scrap in all probability [8].

7. MEASURING SYSTEM

In examinations carried out so far the results of several cutting tests were represented within the framework of a process analysis and the correlations between cutting parameters and resultant forces, chip form, sound emission, coolant pressure as well as the necessary driving power were worked out. The schematic measuring set-up of these tests can be understood with Fig. 12.

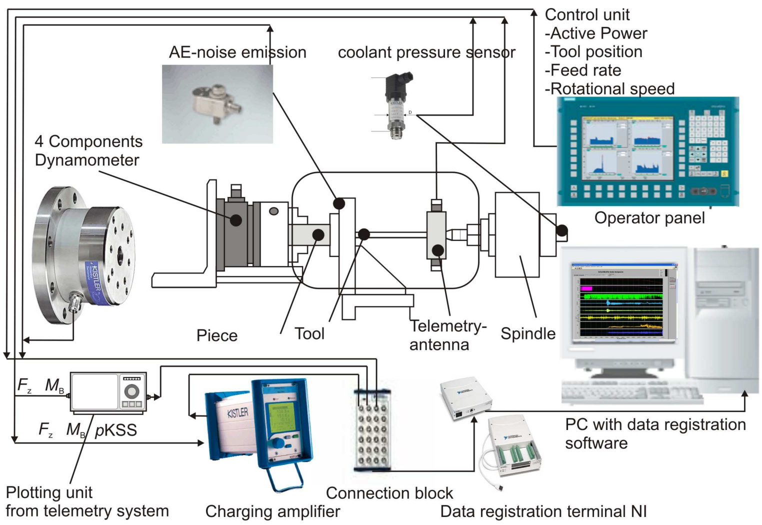

Fig. 12. Scheme of the measuring system used

8. TESTS AND RESULTS

Guaranteeing a stable and economical gun drilling process by using optimised machining parameters has to be seen in connection with all sorts of components of the entire technological system. Hence process and tool parameters as well as coolant characteristics were included in the tests here to optimise the process.

It can be derived from the knowledge gained that the greatest process stability and economic efficiency as well as a reliable and dependable chip removal can be achieved with high cutting speeds and optimised coolant pressures. As feed rate rises, the chip length increases together with the additional tool load due to a more difficult chip removal.

The results gained show that it is possible to realise a process monitoring in gun drilling with tool of 1.8 mm diameter despite low signal levels and short periods of time between the occurrence of disturbances and the subsequent tool breakage. As Fig. 13 shows, different signals such as feed force can be used for that.

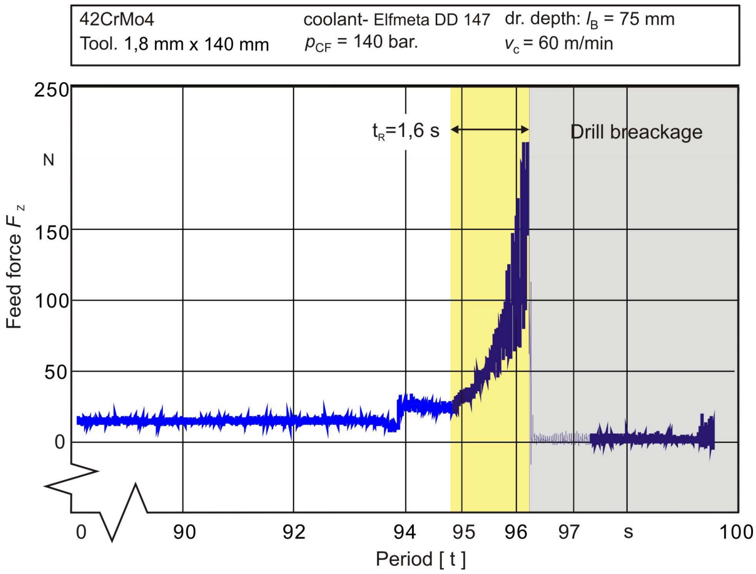

Fig. 13. Forward feeding force for transiting different materials with time to react before rupture of drill

The conducted examinations guarantee optimised drilling strategies, which can be optimised further depending on which diameter and process parameters are used. The application of these drilling strategies revealed a clear reduction in machining or cycle time if the process is stable. The signals determined change noticeably in the case of process disturbances such as chip cloggings, chip crowding and resulting drill breakages. The respective disturbance can also be identified and evaluated here from the course and the level of the signals. It was found that connections with arising process disturbances also show in the signals of tool or workpiece vibrations as well as of acoustic emissions. Hence these were considered to be suitable for the use in process monitoring. When the process monitoring is examined in connection with the use in a transfer line, the signals of coolant pressure and acoustic emission seem to be suited best here. Difficulties still arise, however, in identification and evaluation because of the signal complexity.

The force signals measured in the time frame were converted to the frequency range by means of vibration analysis. Thus the characteristic vibrations of each single drilling phase could be exactly measured and classified. Stable and unstable vibration conditions can be deduced for the gun drilling tool during the process with the transformation (spectral energy density) of feed force signals into the frequency range (see Fig. 14). If the limits of stability are exceeded at a feed rate of v_f = 250 mm/min, the tool predominantly vibrates in a higher amplitude range. The ranges can be clearly distinguished from each other. Moreover, at a feed rate of v_f = 150 mm/min the amplitude is clearly lower and characterises a stable drilling process. A vibration analysis can be realised with online monitoring during the process. An amplitude range can be established as limit here, and a warning signal can be given to the control at the same time. The drilling process can be stopped, and hence a tool breakage can be avoided in time.

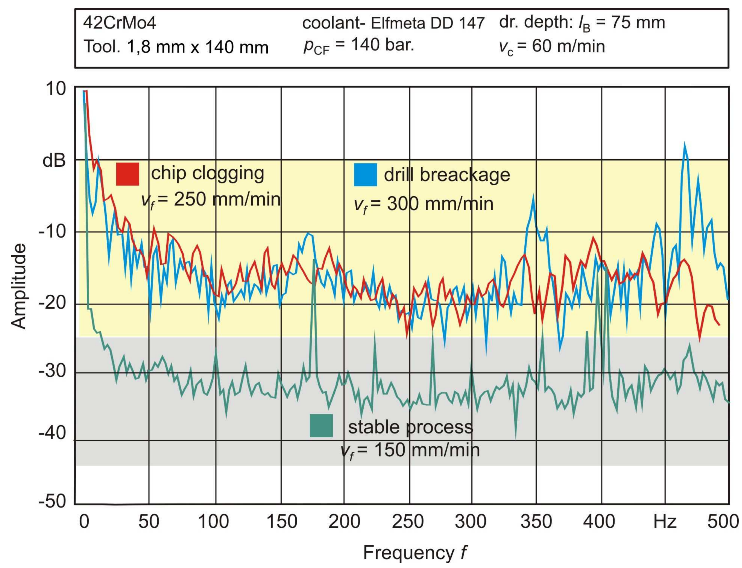

Fig. 14. Transformed feed force signals in stable and unstable gun drilling processes

9. SUMMARY

In summary one can say for the process disturbances in gun drilling, particularly of smallest diameters, that changes in process stability and resulting process consequences can have many different reasons. In addition, process disturbances occur very often depending on each other or else do overlap in practice.

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