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Ultrasonic assistance to reduce and monitor tool wear in deep drilling

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Abstract

In deep drilling, the large aspect ratio of hole depth to diameter causes problems in terms of chip formation and removal as well as tool vibrations. In addition, tool wear leads to a deterioration of process properties and decreasing process reliability. Therefore, scientific approaches aim to improve productivity and quality via a reduction of tool wear. Furthermore, methods for monitoring process conditions, specifically known as tool condition monitoring, contribute to an increase in performance. Superimposing ultrasonic vibrations to the conventional process is known as an approach with various potentials like reduced tool wear and burr formation or enhanced chip breaking behaviour. Aiming to realize in-process measurements to identify tool conditions, ultrasonic assistance enables the application of new monitoring techniques. In this context, the paper introduces a new approach to monitor tool wear using characteristic values of the resonant ultrasonic system coupled with the machining process. Experimental investigations considering deep drilling in steel 1.2311 show prove of the positive influence of ultrasonic assistance on the progress of tool wear. Furthermore, in-process measurements demonstrate that the new approach is able to monitor tool wear.

Deep hole drilling, In-process measurement, Monitoring, Ultrasonic

1. Introduction

Deep drilling with single lip tools is a well-established precision machining process to produce holes with a high aspect ratio of hole depth to diameter, e.g. for manufacturing dies or medical components. Compared to alternative processes, for example electrical discharge machining (EDM), deep drilling provides high productivity and hole quality especially low surface roughness. The process is limited due to problems regarding tool vibration as well as chip formation and removal, that increase with progressing tool wear. Therefore, methods to reduce tool wear lead to enhanced process performance in terms of productivity, quality and cost efficiency. Furthermore, in-process monitoring of tool wear enables optimal utilisation of tool life, high process reliability and the application of adaptive process control.

Ultrasonic-assisted drilling (UAD) is a known approach to improve process performance through enhanced chip breaking [1, 2], reduced burrs [3, 4], process forces [5, 6] or tool wear [7, 8]. With regard to ultrasonic-assisted deep drilling (UADD) Potthast et al. [9] highlight the particular suitability of the approach due to addressing the characteristic problems of the process directly. Nevertheless, there are only few investigations of UADD with single lip drills. Heisel et al. [10] prove the positive affect on chip breaking behaviour and drilling torque in copper E-CU57. Neugebauer et al. [11] investigate UADD in cast iron EN-GJS-800 with minimum quantity lubrication. The experimental results show improved chip removal and the potential to increase of tool life. In summary, the effects of UADD with single lip drill are not well investigated.

Regarding monitoring of machining processes tool condition is a key issue. Jantunen [12], Rehorn et al. [13] and Teti et al. [14] summarize methods for tool condition monitoring. Considering tool wear, the techniques use the effect of increasing process forces or vibrations over tool life. In this context, forces and torque are measured directly with dynamometers [15] or indirectly with the use of spindle current [16]. Additionally, the use of acoustic emission (AE) is a suitable approach to identify tool condition [17]. In summary, the existing approaches are limited in terms of their integration effort as well as their sensitivity and their flexibility to different machining properties and especially their suitability for deep drilling with small diameters.

Therefore, the paper aims to investigate the influence of UADD with single lip drills on machining properties especially tool wear. Furthermore, characteristic values of the ultrasonic vibration are used to develop a new method for in-process tool condition monitoring. Thus, the paper outlines the theoretical background of the monitoring approach. Experimental investigations of UADD in steel 1.2311 with a single lip drill (diameter 6 mm) are carried out and evaluated considering chip breaking, tool wear and the suitability of the monitoring approach.

2. Approach for tool wear monitoring

Transducers for the excitation of ultrasonic systems usually contain piezoelectric elements to perform the electromechanical transformation of electric energy into the ultrasonic vibration. Ultrasonic systems operate in resonance to generate sufficient amplitudes. Moreover, modern devices also include a closed loop control for frequency and amplitude to ensure resonance excitation and a constant vibration amplitude.

According to the research of Littmann [18], the operating behaviour of ultrasonic piezoelectric tranducers near resonance can be described with an electromechanical four-pole model (Figure 1) including voltage $\underline{U}$, current $\underline{I}$, ultrasonic velocity $\underline{v}$ and force $\underline{F}$. The electric domain contains the resistance R_p and capacity C_p of the piezoelectric element. The mechanical domain includes the row circuit of the one dimensional resonance system expressed by a damper d, a mass m and a stiffness c. Both domains are connected via an ideal transformator displaying the electromechanical transformation with the coefficient n. In addition, the mechanical load during operation can be linearized and expressed by the process damping d_L and stiffness c_L.

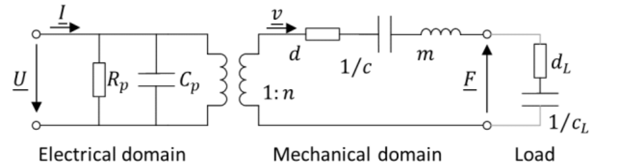

Figure 1. Electromechanical model of a transducer [18]

The stiffness c_L causes an increase of the resonance frequency and therefore also of the operating frequency of the ultrasonic system from the unloaded frequency $f_{US,F}$ to the loaded frequency $f_{US,L}$. Regarding UAD, c_L defines the contact stiffness of the tool including the cutting edge to the material of the workpiece. In this context, the value depends on the contact surface as well as on the static contact force. With respect to monitor tool wear in cutting processes, especially in deep drilling, c_L is a suitable key value to represent the wear progress, which causes increased process forces as well as a change of the contact surface. Based on equation (1) [18], c_L is defined by the stiffness c and the frequency of the unloaded condition $f_{US,F}$ and the loaded condition $f_{US,L}$.

$$\frac{c_L}{c} = \frac{{f_{US,L}}^2}{{f_{US,F}}^2} - 1 \qquad (1)$$

Figure 2 shows a typical graph of the operating frequency in UADD. The ultrasonic generator starts in section I with a scan to find the resonance frequency, which is constant for the unloaded tool condition in section II. When starting the drilling process in section III, the frequency increases. After the first part of the hole, which is, especially for deep drilling, defined by a specific parameter regime, the drilling parameters are constant and the operating frequency reaches a constant level representing the loaded condition.

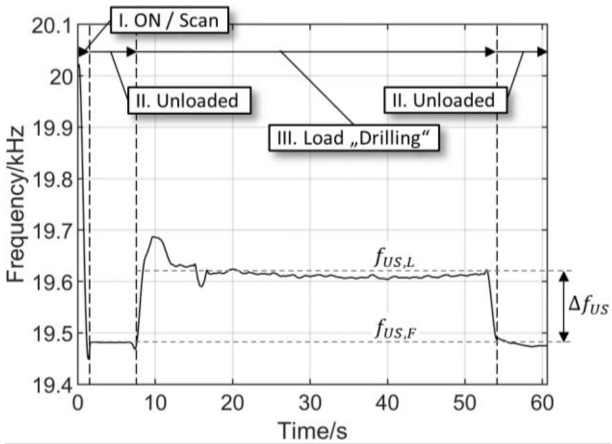

Figure 2. Typical frequency course in UADD

To avoid the parameter identification procedure of the entire values of the electromechnical modell the approach for in-process tool wear monitoring focusses on tracing of the resonance respectively the operating frequency. In this context, the increase of the operationg frequency Δf_{US} according to equation (2) is suitable to represent the tool load as well as the wear status.

$$\Delta f_{US} = f_{US,L} - f_{US,F} \qquad (2)$$

In practical application there are different ways to measure and calculate the operation frequency. Ultrasonic generators provide a log function. Aiming to develop an in-process measurement system with a high resolution output voltage or current of the generator are suitable measurement values, because the sinusoidal courses contain the frequency information. Considering the limitation of previous monitoring techniques this new approach provides a value that is representative for tool load and wear directly in the process zone without the implementation of additional sensors inside the working area of the machine tool.

3. Experimental setup and design of experiments

Figure 3 shows the experimental setup with the used deep drilling machine (AX1 TL, Ermafa GmbH Auerbach) including the ultrasonic tool holder to superimpose the vibration in feed direction. The self-developed system consists of an ultrasonic generator, an inductive energy transmission and a tool holder with an integrated piezoelectric tranducer. The closed loop control of resonance frequency and amplitude is based on a sensor measuring the mechanical vibration inside the transducer. A radio transmission unit sends the signal to the generator, which performs the closed loop control.

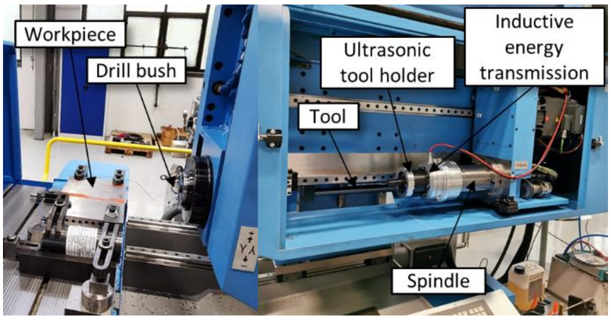

Figure 3. Experimental Setup

The tool was a solid carbide single lip drill with a diameter of 6 mm. The workpiece material was steel 1.2311. The deep drilling experiments included two test series. The first one compared conventional deep drilling (CDD) with ultrasonic-assisted deep drilling. Table 1 shows the parameters of the test series, which contained a variation of the feed velocity v_f between 100 mm/min and 300 mm/min in steps of 25 mm/min. While 125 mm/min defines the industrial standard, the objective of the parameter variation was to compare CDD and UADD regarding chip breaking behaviour and process stability. Furthermore, for UADD an evaluation of the correlation between feed rate and increase of the operation frequency Δf_{US} aimed to indicate the capability of the monitoring approach to represent the process load.

Table 1 Parameters of test series 1

	CDD	UADD
Tool diameter x length / mm	6 x 300	6 x 300
Drilling depth / mm	160	160
Spindle speed / min^{-1}	2700	2700
Cutting speed / m/min	51	51
Feed velocity / mm/min	100…300	100…300
Feed rate / mm	0,037…0,111	0,037…0,111
Lubrication pressure / bar	oil ≈100	oil ≈100
Vibration amplitude / µm	0	5,7 (peak-peak)

The second test series used fixed parameters within a feed velocity of 125 mm/min according to Table 1 and aimed to compare tool wear in CDD and UADD. For this purpose, the tool wear, especially the wear marks on the flank, was evaluated with an optical microscope over 110 holes each. Additionally, for UADD, the progress of tool wear and Δf_{US} were investigated to evaluate the suitability of the monitoring approach.

In order to calculate the operating frequency, the output voltage of the ultrasonic generator was measured with a differencial probe TT-SI9110 from Testec Elektronik Gmbh. The analog signal was digitalized with an APOLLO Box from SINUS Messtechnik GmbH and a sample rate of 200 kHz. The signal processing was performed in MATLAB®, which also provides an interface for real-time calculation in combination with the measuring device. To identify the ultrasonic frequency a Short-time Fast Fourier Transformation (STFFT) was used. In frequency domain, the highest amplitude indicates the operating frequency. In addition, the unloaded and loaded operating frequency were calculated as mean values over the according section II and III. The increase of the frequency Δf_{US} was calcaulated with equation (2).

4. Experimental results and discussion

4.1. Feed rate test series

During feed rate tests, the results indicate that UADD leads to higher process stability. This is related to subjective perception of audible noise. During UADD the characteristic noise of the deep drilling process disappears. Further measurements with an acceleration sensor, not included in this paper, prove the assumption of the disappearance of tool vibrations. Figure 4 shows chips produced by CDD and UADD. Especially for these parameters UADD leads to significantly shorter chips with an improved ability for chip removal, which prevents chip jamming and process instabilities. This effect corresponds to previous investigations of UADD and is beneficial particularly for the drilling of deep holes.

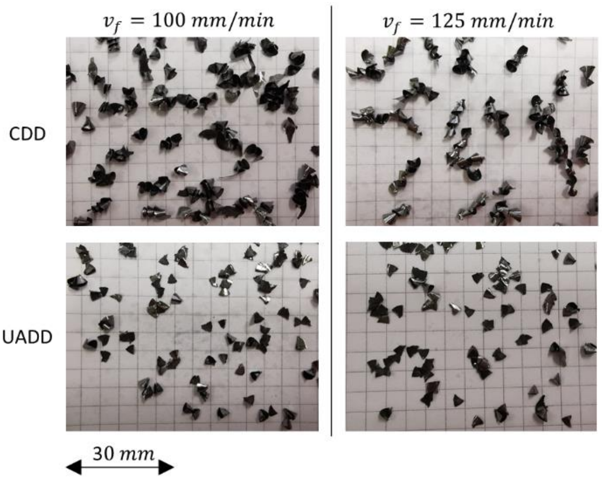

Figure 4. Comparison of chips in CDD and UADD

The theory of cutting technology outlines a clear correlation between feed rate and process forces. Aiming to identify the capability of the monitoring approach to represent the process load, Figure 5 shows the relation between Δf_{US} and feed velocity v_f. The graph shows a clear correlation. Higher values of v_f cause an increase of Δf_{US}. This indicates that Δf_{US} is sensitive to the process load and suitable for the monitoring of tool wear.

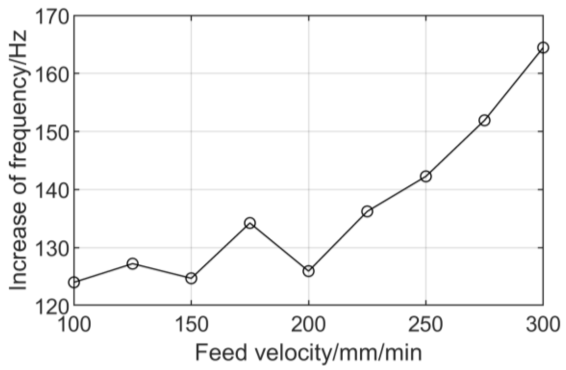

Figure 5. Relation between Δf_{US} and v_f for UADD

4.2. Tool wear test series

The evaluation of tool wear focused the marks on the flank face of the outer part of the main cutting edge. Figure 6 shows pictures of the flank face for CDD and UADD for the new tool and after 40 holes. Figure 7 shows the tools after 80 and 110 holes. Regarding the progress of tool wear clear trends are visible. The wear marks of UADD are significantely smaller than in CDD. Furthermore, the build-up edge is reduced. In addition, for CDD a small chipping occured at the centre of the tool after 20 holes.

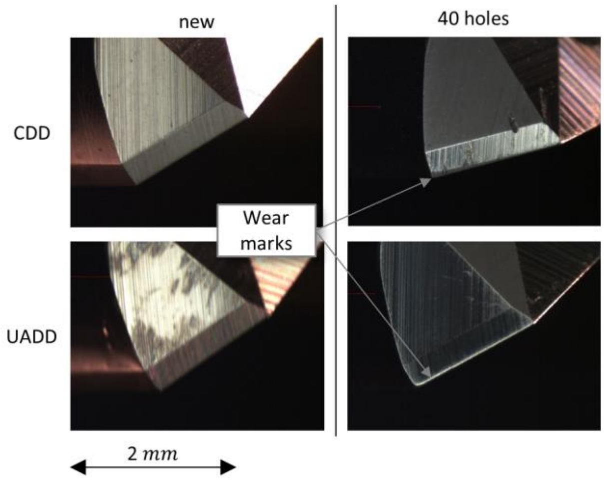

Figure 6. New tool and flank wear after 40 holes

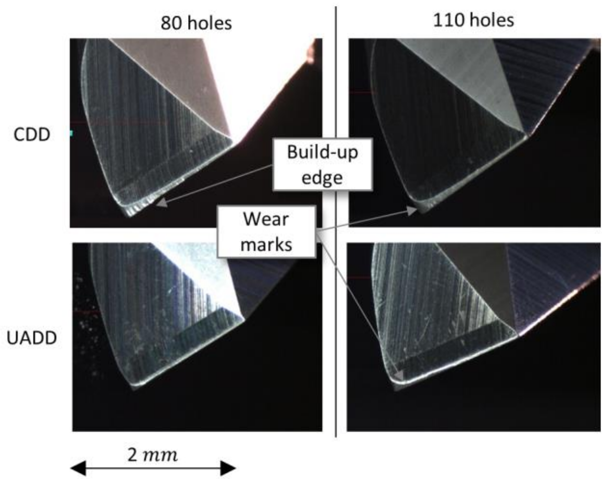

Figure 7. Flank wear after 80 and 110 holes

Additionally, the width of the wear marks was measured to describe the maximum value VB_{max} as well as the mean value VB_{mean}, consisting of five measuring points at the outer part of the flank. After 110 holes the CDD tool showed values of $VB_{mean} = 116{,}2\ \mu m$ and $VB_{max} = 286\ \mu m$. The UADD tool had values of $VB_{mean} = 75{,}6\ \mu m$ and $VB_{max} = 156\ \mu m$. In comparison to CDD, UADD leads to a reduction of the mean width of 35 % and of the maximum flank wear of 45 %. Figure 8 shows the progress of VB_{max} over the number of holes. The results clearly show that UADD leads to a significant reduction in tool wear and therefore contributes to enhanced process properties and cost efficiency of deep drilling with single lip tools.

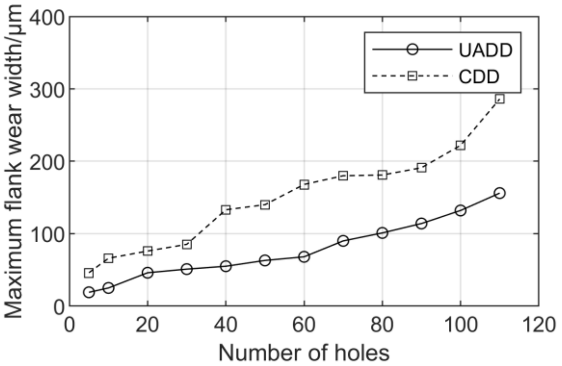

Figure 8. Comparison of VB_{max} over the number of holes

Second objective of the tool wear analysis was to compare the results with the behaviour of the frequency value Δf_{US}. Figure 9 shows the progress of Δf_{US} over the number of holes and Figure 10 the relation between Δf_{US} and the flank wear VB_{mean}.

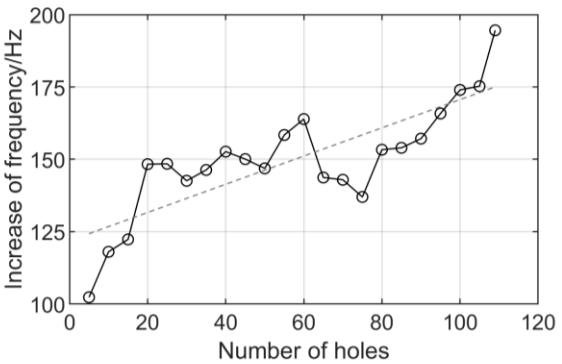

Figure 9. Increase of operating frequency over number of holes

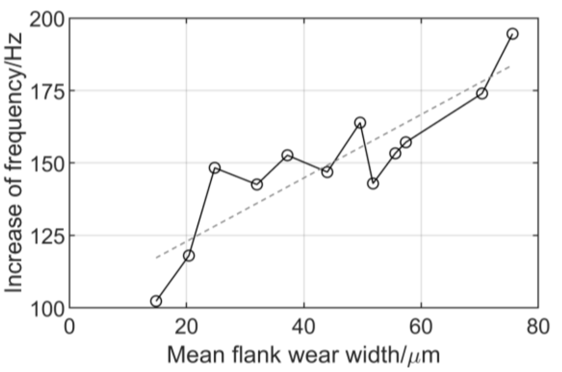

Figure 10. Increase of operating frequency over flank wear

Considering the overall trend, the frequency increases over the number of holes with a good correlation to a linear relation, comparable to the progress of flank wear. The results in Figure 10 indicate a clear connection between Δf_{US} and the mean value of the flank wear VB_{mean}, which is required for a key value of a monitoring system. In good agreement, this relationship can be well represented by a linear trend. This proves the suitability of the novel approach using the resonance respectively the operating frequency of the ultrasonic system for in-process monitoring of tool wear. It should be noted that the use of this approach relies on frequency control and therefore requires reliable control behavior. By using this method, no additional sensors need to be integrated into the machine although, in relation to the contact stiffness c_L, the measuring point is located directly in the process zone respectively on the tool tip.

5. Conclusion

This study aimed to investigate the influence of ultrasonic assistance on the tool wear in deep drilling of steel 1.2311. Furthermore, a new approach for in-process monitoring of tool wear using the coupling of the resonance vibration system with the cutting process was presented and evaluated regarding its suitability. Experimental test series showed that UADD leads to significantly shorter chips, improving the chip removal as a key issue in deep drilling. Additionally, UADD had a strong impact on tool wear. Compared to CDD, after 110 holes the mean width of the flank wear was reduced by 35 % and the maximum width by 45 %. Based on these observations, it was demonstrated that ultrasonic assistance contributes to a significant improvement of the deep drilling process. The introduced approach to use the operation frequency for process monitoring showed satisfying results. The value is sensitive to feed rate and process load. The correlation, especially the good agreement with a linear relation, to the mean value of the flank wear width proves the suitability for in-process tool condition monitoring.

Future research should focus on wide parameter studies of UADD to confirm the results for different applications. Furthermore, the process monitoring approach should be subjected to a detailed sensitivity analysis, especially of the dependencies to the process forces, the contact surfaces of the tool and the behaviour of the frequency control.

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