Monitoring Tool Wear in Drilling Process Using Spindle Noise Features

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***Abstract*—The use of worn cutting tools has a detrimental effect on the surface finish of a workpiece, tool precision and internal machine stress. Worn tools also decrease productivity through unplanned stops, tool changes and increase the production of scrap material. This study investigates an inexpensive and non-intrusive method of inferring tool wear by measuring the audible sounds emitted during a drilling process. A microphone was used to record the machining operation sound of S50C steel, which was drilled using a computer numerical control (CNC) milling machine in wet conditions. The audio signature was examined using a spectrogram, and the extracted sound features of the rotating spindle motor in the frequency domain were used to correlate with tool wear. The results indicated that the frequency of spindle noise was unrelated to tool wear, but although the magnitude of spindle noise significantly increased in accordance with tool wear progression.**

***Index Terms*—tool wear monitoring, wear monitoring, drilling, spindle noise**

I. INTRODUCTION

The machining process is one of the important manufacturing processes commonly used to produce semi-finished and final products by changing the geometry of bulk materials. Cutting tools typically remove material in the form of chips. Although recent developments in cutting tool materials and tool control technology have led to an increase in tool life, the tools still wear out over time. Tool wear has a direct influence on the surface finish, precision, and accuracy of the workpiece, which tends to increase the rejection rate.

In fully-automated machining processes or machining environments with a small number of operators, increasing the tool's useful life and damage from excessive tool wear or tool breakage can make the process more cost-effective. In addition, tool replacement and unplanned stoppages attributed to worn tools can cause machine downtime and part non-conformance, which leads to economic loss. This issue can be resolved with an effective tool condition monitoring system.

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Many of the recently developed systems reviewed by Rehorn *et al.* [1] and Abellan-Nebot *et al.* [2] use expensive sensing systems (such as force dynamometers, acoustic emission (AE) sensors and associated data acquisition hardware), which are often unsuitable for use in an actual production environment, particularly with respect to their physical robustness and cost. Virtually all of these monitoring systems were developed in a controlled laboratory environment (dry machining conditions). As these experiments attempt to accelerate tool wear to minimise time and costs, actual performance in real machining conditions (wet machining) is typically lower. Therefore, the development of an inexpensive tool-wear monitoring system would greatly enhance many machining processes

A microphone is an inexpensive sensing device that has rarely been used to monitor tool wear in machining processes due to uncontrollable interference from surrounding noise in the local environment. Previous attempts have used a microphone to record machining sound in dry machining conditions so that noise interference from the cooling liquid was eliminated [3-5]. In addition, the use of such method in a wet machining conditions was developed and reported by Seemuang *et al.* [6] where a novel sensing feature extracted from the cutting sound, referred to as 'spindle noise', was successfully used to detect excessive tool wear in a turning process. With this in mind, our study examines whether spindle noise alone can indicate the state of tool wear in a drilling process without expensive monitoring systems, such as AE and dynamometers.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. *Equipment and Drilling Conditions*

A CNC milling machine (VMC-1100S) was used to drill S50C steel blocks with a dimension 300 x 300 x 75 mm machined from billet. The chemical composition of the S50C steel is presented in table I. The workpiece was fixed on the machine table using four clamps prior to drilling. All drilling trials were conducted using a high-speed steel drill bit with a diameter of 10.0 mm. More

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severe cutting conditions than those typically used for selected drill bits were chosen to accelerate tool wear and use less raw material. The cutting parameters included a constant cutting speed (Vc)=30 m/min or 956 rpm, and a feed rate (F)=0.14 mm/rev. The constant hole depth was set at 35 mm, and the drilling point was cooled with Shell Dromus Oil B for all drilling trials to prolong tool life and effectively remove chips.

A microphone (PCB-130E21, with a frequency response of 20–10,000 Hz) was used to record drilling sounds during the process. The arrangement of the microphone is shown in Fig. 1 The microphone (in an enclosure box) was directly connected to a National Instruments NI-9234 DAQ and mounted on the machine table by a magnetic stand located 80 cm perpendicularly away from the centre of the workpiece in order to prevent the damage from coolant spray. The sound signal was sampled at 50 kS/s using National Instruments LabVIEW software and then processed by Matlab. All recorded sound was transformed into the frequency domain using Fast Fourier Transform (FFT)

TABLE I. CHEMICAL COMPOSITION OF JIS S50C STEEL BLOCK (%WT, %FE BAL.)

C	Si	Mn	P	S
0.47~0.53	0.15~0.35	0.60~0.90	0.03 max	0.035 max

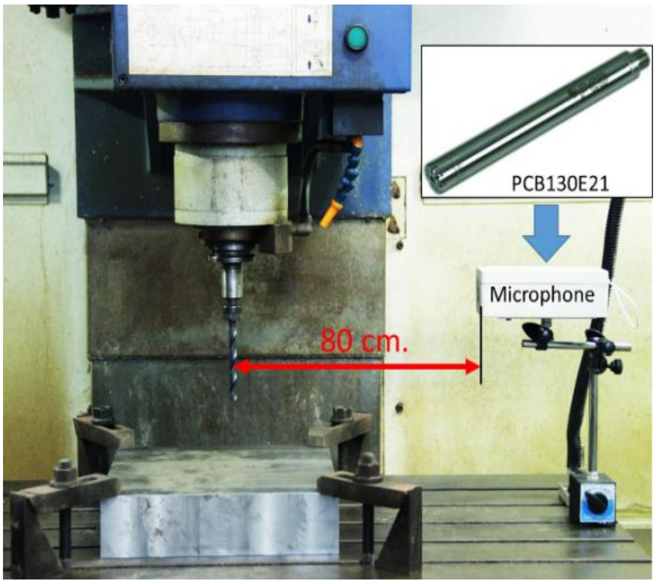

Figure 1. Experimental setup

B. Experiment Methodology

The HSS drill bit was used to drill the 10 mm holes on S50C until excessive average flank wear on the cutting edges exceeded 0.5 mm. To obtain flank wear values, the drill bit was removed from the tool holder and average flank wear on the cutting edges was measured using an optical microscope. The measurements were recorded more frequently as the wear approached 0.5 mm, and the final wear of the drill bit was then inspected, as shown in images from the experiment presented in Fig. 2.

The audio activity during drilling was analysed using a spectrogram to identify spindle noise features extracted from the sound signal, which were subsequently correlated with tool wear progression.

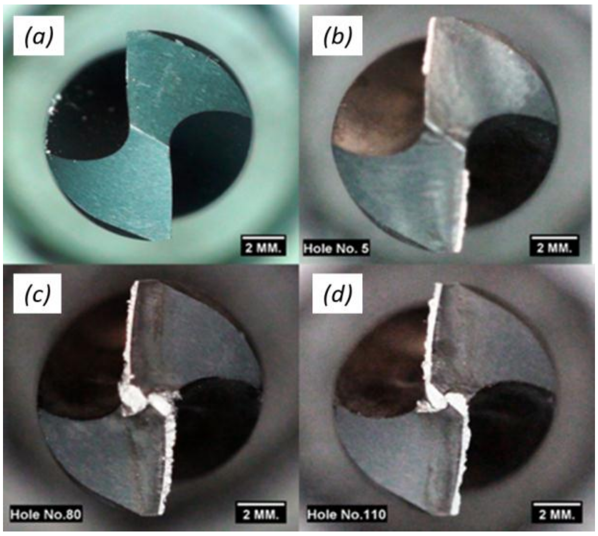

Figure 2. Tooltip micrographs displaying tool wear on a drill bit (a) new tool, (b) at hole number 5, (c) at hole number 80 and (d) at hole number 110

III. RESULTS AND DISCUSSION

A. Sound Activity during Drilling Process

In the drilling experiment, many sources of sound were recorded by the microphone, including machine tool spindle, drives, coolant spray, the cutting mechanism, and adjacent working machines. To identify the sound sources, the time-frequency domain based on short-time Fourier transform was used to observe sound activity and generate a spectrogram. An example of the drilling sound recorded from one drilling cycle was transformed into the spectrogram presented in Fig. 3. The horizontal axis represents drilling time, while the vertical axis displays frequency. The amplitude of particular frequencies are represented by the colour intensity of each point.

The spectrogram indicated that the sound signal was contaminated with environmental sound, referred to as machine background noise (A), which has a low frequency in the range of 0-3 kHz and depends on the particular machine. This is consistent with several studies

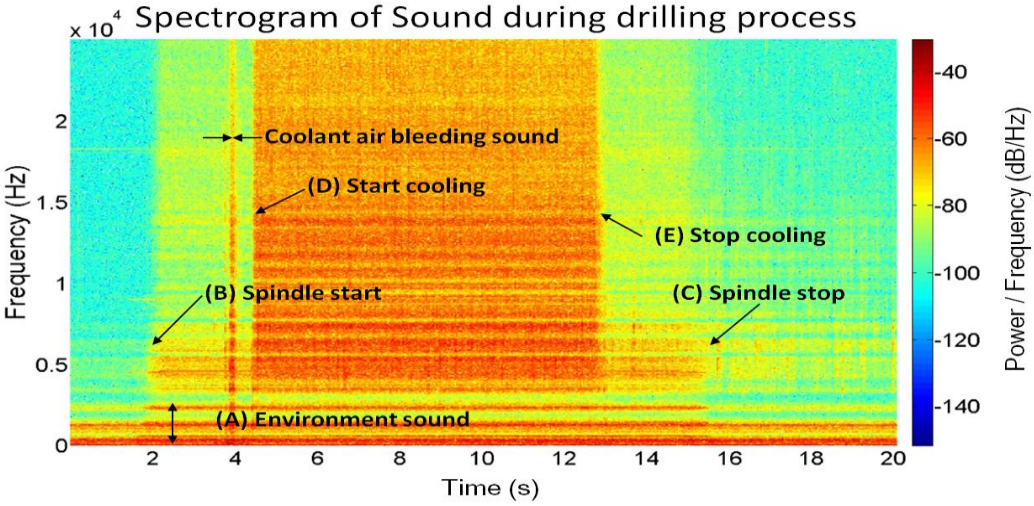

Figure 3. Spectrogram of sound during drilling process

mentioned in Seemuang *et al.*[6]. Point B indicates the activation of the spindle motor , which accelerates to the setup speed, and point C indicates the spindle stoppage. Since the drilling experiment was performed in wet conditions, a broadband frequency of coolant was applied to the drilling point illustrated in the spectrogram from (D) to (E). Air bleeding in the coolant tube had suddenly sounded before the cooling liquid was supplied to the drilling point, and the noise from the main spindle motor was found at approximately 4-5 kHz, as shown in the FFT graphs in Fig. 4.

B. Effect of Cutting Condition on Spindle Noise

The changes in frequency and the magnitude of spindle noise were analysed by FFT. This analysis was repeated for random cutting conditions (both cutting speeds and feed rates). It was found that the spindle noise in this drilling experiment was detected at approximately 4.5 kHz regardless of cutting conditions, while the spindle noise reported in the turning experiment was 5.86 kHz [6]. Additionally, the sound intensity (magnitude of the spindle noise frequency) increased significantly with an increase of in the number of cutting parameters. Figs. 4 – 6 present the FFT graphs of the sound signal obtained for different drill bit diameters: 7.5, 10 and 12.5 mm. Results of our experiments indicated there was no correlation between the frequency of spindle noise and the diameter of drill bits used (constant frequency of 4.5 kHz), but the use of larger drill diameters resulted in a higher magnitude of spindle noise frequency, as shown in Figs. 4 – 6. This may have been due to the high metal removal rate created by the larger drill diameter, as the spindle motor emits a higher magnitude of spindle noise frequency when under higher loads. This suggests that only the magnitude of spindle noise frequency has a potential to be used for tool wear monitoring.

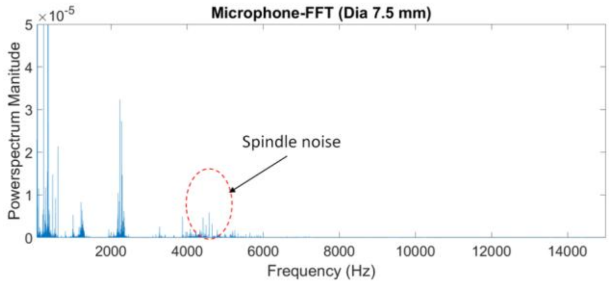

Figure 4. Power spectrum Magnitude of drill bit diameter 7.5 mm

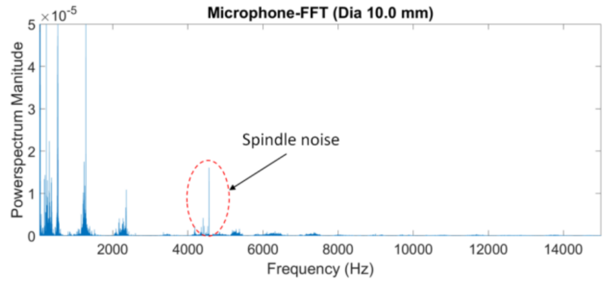

Figure 5. Power spectrum Magnitude of drill bit diameter 10.0 mm

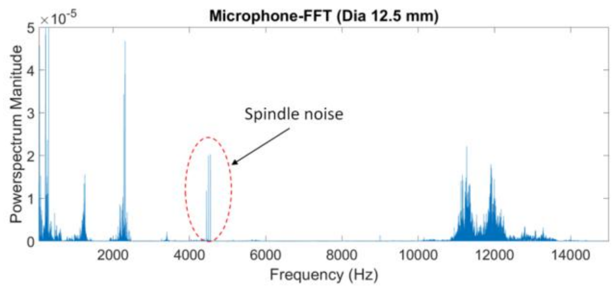

Figure 6. Power spectrum Magnitude of drill bit diameter 12.5 mm

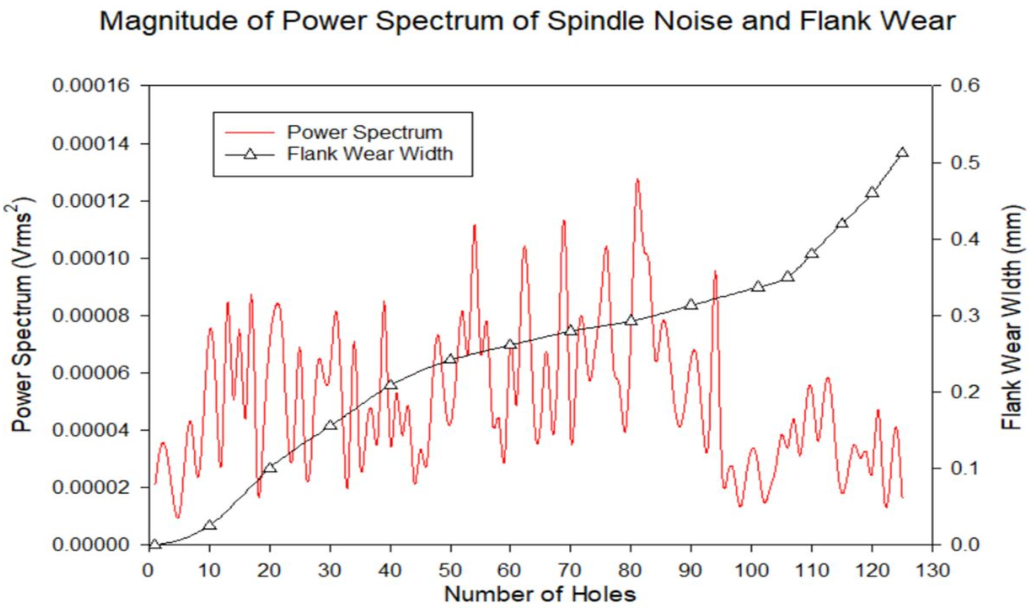

Figure 7. Progression of magnitude of spindle noise frequency and average flank wear

C. *Correlation between Magnitude of Spindle Noise and Tool Wear*

To establish the relationship between the magnitude of spindle noise and tool wear, a total of 128 holes were drilled (at Vc=30 m/min, F=0.14 mm/rev). It was assumed that this amount of drilling assumed would result in a failure wear state or the progression of drill bit wear could be found. The spectrum magnitude of spindle noise frequency was observed and compared with the progressive flank wear, which was measured by the microscope, as shown in Fig. 7. The number of holes drilled associated with drilling time was used to represent the progressive wear of the drill bit.

It can be seen that the spindle noise frequency of a new tool has a low magnitude in the power spectrum (hole numbers 1–20), and the magnitude increases as the tool was used. On average, the magnitude of the power spectrum gradually increased, which correlated with an increase in drill bit wear. Compared to the turning experiment [6], in which the magnitude of spindle noise significantly increased in the middle of the steady-state wear region and decreased significantly when the tool was worn in the failure wear region, the magnitude values in the drilling process fluctuated. This may have been due to the variation in the distance between the microphone and the drilling position and the superposition of the spindle sound waves, which varies with changes in drilling and any other undefined variation.

Similarly, the magnitude of spindle noise was low when the drill bit lost its ability to cut, as seen with hole number 95. It was assumed that an increase of cutting resistance caused by using worn tool results in a high thrust force required for drilling the workpiece. This was confirmed by the observed increase in power consumption by the feed motor on the CNC machine. A high thrust force can affect the spindle mechanisms, and the magnitude of this spindle noise frequency would thus be lower in final tool wear state. However, this increasing trend and sudden drop of spindle noise frequency magnitude could be used to monitor the drill bit wear if sound signal processing was improved, or if any variation was eliminated. Further research is necessary to investigate this possibility.

IV. Conclusion

The drilling experiment was performed to identify whether the tool wear monitoring feature, referred to as 'Spindle noise', can be applied to the drilling process in the same way it was previously employed in a turning process. The conclusions of this work include the following:

1. The noise from the spindle motor during the drilling process was detected at a constant frequency of 4.5 kHz, and the noise from the machine itself was between 0–3 kHz for this particular machine.
2. There is no distinct correlation between the frequency of spindle noise and the cutting parameters, the size of drill bit, or tool wear.
3. The magnitude of the power spectrum for spindle noise could be used to monitor tool wear as it increases in accordance with tool wear.

In summary, this work has shown that simple and inexpensive instrumentation can be used to monitor tool wear under wet drilling condition.

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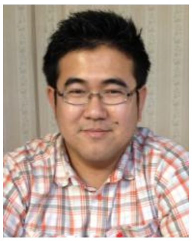

Nopparat Seemuang completed his Ph.D. in mechanical engineering from the University of Sheffield, UK in 2016. During this time, he conducted research on the development of non-destructive systems to monitoring cutting tool conditions in collaboration with the Advanced Manufacturing Research Centre (AMRC) in the UK. He is now a lecturer in the Department of Production Engineering, KMUTNB, Thailand. His current focus in the development of condition monitoring systems for machining and forming processes.

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