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Tool Wear Inspection of Polycrystalline Cubic Boron Nitride Inserts

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ABSTRACT

Tooling used in machining of safety critical components are seldom used without highly frequent inspection. Worn or damaged tools produce undesirable surface finishes leading often to early failure of the part due to fatigue crack growth. In the development stages of polycrystalline boron nitride tools, an off-line run-to-failure method of tool wear inspection is undertaken which interrupts the cutting process intermittently to measure the tool wear using optical and scanning microscopy. The time consumption of this method leads to expensive tests and bottlenecks in the workshop. The overall aim in industry is to develop an on-line, automated system which is capable of informing the operator of the tool′s imminent failure. This paper focuses on treating this process as a preventative maintenance problem by studying whether acoustic emission can be used as an indirect measurement of tool wear at any given time. Acoustic emission measurements taken from the machining process of face turning are investigated here. Basic analysis in the frequency domain using principle component analysis reveals a number of interesting insights into the process. Relationships between the sharpness of the tool and the magnitude of the frequencies suggests promising link between acoustic emission and tool wear.

Keywords: Acoustic Emission, Tool Wear, PCBN, Principle Component Analysis, Turning

1 Introduction

Polycrystalline Cubic Boron Nitride (PCBN) is the second hardest material in existence [1]. For this reason, and due to low wear rates, PCBN is utilised as a cutting tool material. Wear resistance is a crucial property, which allows the tool to operate for longer periods under harsh environments such as high cutting forces, high temperatures, shock loading and plastic deformation [2]. PCBN also has low chemical wear rates, especially when machining ferrous material, as it does not contain carbon molecules, which tend to burn in high temperatures or diffuse into other carbon base workpieces [3]. Subsequently, PCBN can be used for machining hardened steel. At high cutting temperatures (700°C or higher), the high thermal conductivity of PCBN permits the fast dissipation of heat whilst its toughness and strength aids with resisting fracture [4]. These material properties allow PCBN to be used in finish turning which is a way of securing a desirable surface finish of a machined part. This process is capable of replacing grinding in the final machining stage, and consequently, of reducing the cost and time required for finishing [5] .

Owing to the aforementioned material characteristics, PCBN is expensive compared to carbide tooling [6]. Therefore, the preventative method used in industry where tools are discarded at constant time intervals can be costly. Currently, this technique is used because it is not possible to directly measure the tool during cut to investigate its wear state. During the cutting process, the tool is always in contact with the workpiece, and the area of contact is very small. Hence, accessibility poses as the main obstruction of directly measuring tool wear. However, studies undertaken on tooling materials such as carbides and ceramics for example, have found tool wear to influence the forces, temperatures, acoustic emissions and vibrations generated in machining [7–9]. Therefore, by measuring these outputs, tool wear can be studied indirectly. The approach taken here is to use the indirect measurements in conjunction with tool wear data taken at certain time intervals, for supervised learning, as a first step of automation. In this work, acoustic emission of a PCBN insert was collected during a turning operation. The resulting data were studied in the time and frequency domain, to understand whether this output can be used as an indirect measurement of tool wear of PCBN.

1.1 Acoustic emission during turning

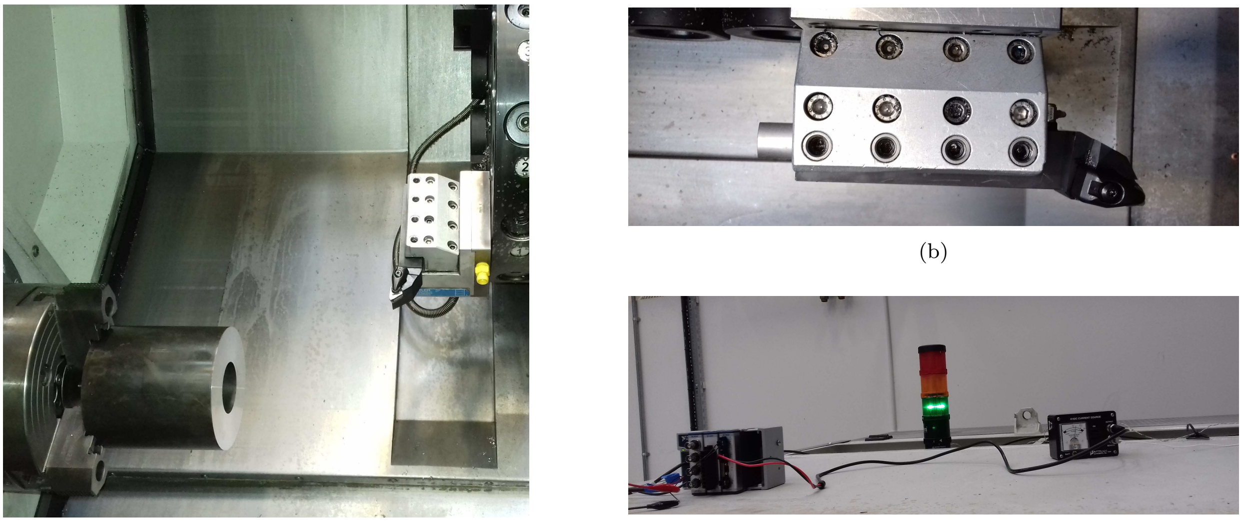
During deformation of a material, elastic energy is released and is named acoustic emission (AE). These stress waves can be captured by piezoelectric transducers. As a non-destructive evaluation method, AE is often used in predictive maintenance of structures and machinery [10]. Although AE is not usually adapted into continuous monitoring systems, it has be employed in attempts to predict tool wear in metal cutting in the past [11–13]. AE signals obtained during machining are made up of both continuous and transient components. The continuous signal is produced by plastic deformation and frictional effects occurring in the cutting zone [14]. Transient signals are therefore an indication of collisions and breakages [15, 16].

Numerous studies have been conducted on examining the AE signal during a tool′s life and many have found that flank wear has a correlation with changing features of AE such as root mean square (RMS), skewness, kurtosis, AE count rate, amplitude and frequency. In literature, it was found that low values of AE amplitude was caused by worn tools, whereas the high values are present owing to sharp tools [17]. Furthermore, as the tool wear increases, the high temperatures generated in the cutting zone leads to a formation of a white layer which could in turn increase the AE values once more, as white layers are harder than the original workpiece surface [17]. It has also been suggested that whilst this is the case, increasing thermal loads leads to lower damping and therefore lower AE amplitude [18].

The use of acoustic emission measurements to understand tool wear in hard turning using PCBN has only been conducted once previously. The study in question was based on basic time domain analysis where the skewness and kurtosis of the signal′s RMS values were compared against flank wear. The author found the shape of the bursts coupled with its amplitude can give an idea of the severity of flank wear but concluded that the results were not reliable or robust enough for practical implementation [19]. Subsequently, this work was carried out in order to understand whether AE signals taken from PCBN tooling, could provide information regarding tool wear states, when analysed in the frequency domain.

2 Experimental set-up

The experimental set up for this work used diamond shaped inserts manufactured with 55% CBN content. The workpiece used was a true hardened steel (AISI 4340) bar with a hardness value between 54 to 57 HRC. In one pass of the face turning operation, the tool travels from the outer diameter (120mm) of the workpiece to the inner diameter (48mm). A CNC lathe, Gildemeister CTX400 was used for this experiment. Piezoelectric AE transducers (Kistler 8152B111) were used with 1MHz sampling rate. The sensor was placed at the back of the tool holder, to minimise the amount of noise captured. A Kistler A5125 pre-amplifier was used without any filters. Figure 2.1 displays the machine and sensor set-up. Wear measurements were taken after every 10 passes. Crater wear images were taken using an Alicona and flank wear images using an optical microscope. The tools were tested in face turning conditions under standard machining parameters.



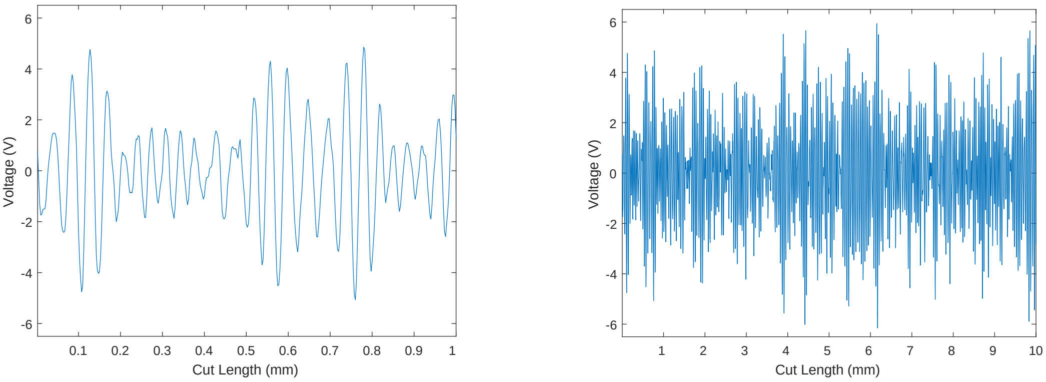
(a) (b) (c)

Figure 2.1: (a) The lathe with the workpiece and tool holder dynamometer with tool holder in place. (b) AE sensor placed at the back of the tool holder. (c) The compact DAQ system (left).

3 Results

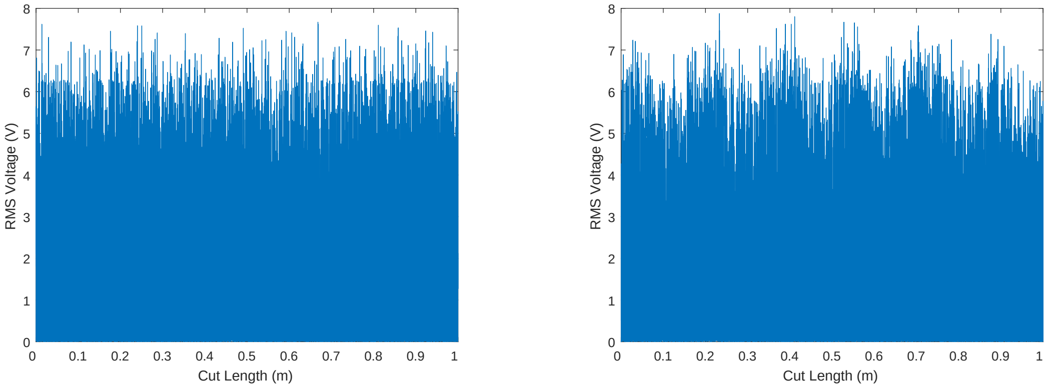
3.1 Time Domain Observations

The face turning operation produces AE bursts continuously throughout each machining pass. Figure 3.1a displays the data captured during a cut length of 1mm. When studying data corresponding to 1mm, roughly 3 wave packets can be seen. These vary in amplitude and duration. When observing the raw data at the 10mm scale (Figure 3.1b), the wave packets seen in the 1mm scale are grouped together at different time scales. At this scale, the literature suggests that the transient, high amplitude pulses are due to collisions of the chips against the tool and the low amplitude continuous waves are due to deformation of the workpiece [20]. In passes from later on in the trial, during a metre of a cut, the amplitude of the AE signal which represents around 160mm, periodically increases and decreases roughly 6 times (Figure 3.2b). This behaviour is not evident in the early stages of the tool (Figure 3.2a) suggesting it is directly linked to tool wear. The root mean square of the signal at the early stages of tool life and the signal from a worn tool displays this effect clearly.



(a) (b)

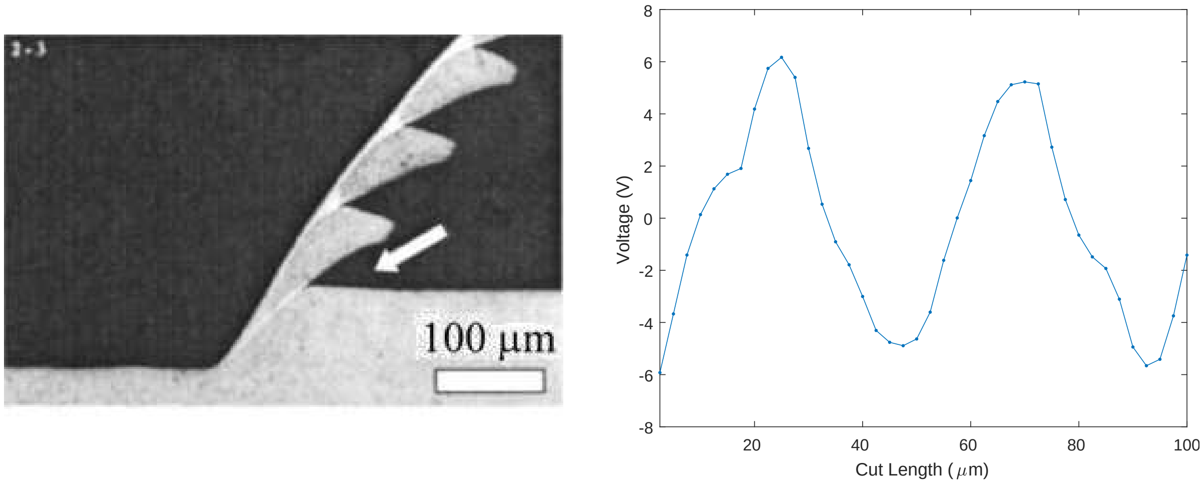
Figure 3.1: Data produced at cut length of (a) 1mm and (b) 10mm.



(a) (b)

Figure 3.2: Data produced at cut length of 1m (a) new tool and (b) worn tool.

The cause of each AE oscillation at the 1mm (Figure 3.1a) scale has not been explained in literature. In the past, these signals have been studied at larger scales than 1mm. However, many studies have been conducted on chip formation when machining hardened steel with cubic Boron Nitride tools. It has been found that at the constant cutting speed of 2.5m/s as used here, the chips produced are saw toothed [21]. This means in the primary shear zone, the chip periodically fails [22]. The frequency of the force oscillation as the saw tooth is formed is around 20 to 50kHz [23]. Past studies have captured this sawtooth shape and it can be seen in Figure 3.3a. For these cutting tools and workpieces, the chip shape is continuous for lower cutting speeds and the sawtooth is sharper for higher cutting speeds. When comparing this chip formation information from literature with the AE data collected in this trial at the cutting speed of 2.5m/s, an interesting relation can be seen. The saw tooth chip formation examined in previous studies occur around every 50μm (i.e the distance between two teeth at the peaks), and the periodicity of the oscillations seen in Figure 3.1a also occur around every 50μm. The corresponding signal showing 100μm can be seen in Figure 3.3b. Subsequently, it could be presumed that one wavelength of the AE signal is produced by the adiabatic shear band growing and breaking in the primary shear zone. However, at this early stage, not enough evidence is available to confirm this assumption completely as chips were not collected in this study.



(a) (b)

Figure 3.3: (a) Sawtooth chip and its formation taken from cutting conditions (V$_c$ = 2.5 m/s, Hardness$_{workpiece}$ = 56 HRC) [24] (b) Signal captured during 100μm.

3.2 Frequency Domain Observations

The AE signal produced during the entire tool life was split into over 1600 sections to reduce computational cost. The frequency component of an AE signal which provides the content of the waveform was calculated using a short time Fourier transform for each section (Figure 3.4). The magnitude is shown in decibels. Principle component analysis was conducted on the magnitude of the AE frequencies of each section. The percentage of variance of the scores (or axis) indicate that almost 90% of the variance can be captured by the first 2 scores which are plotted in Figure 3.5 where the colour bar represents the pass number.

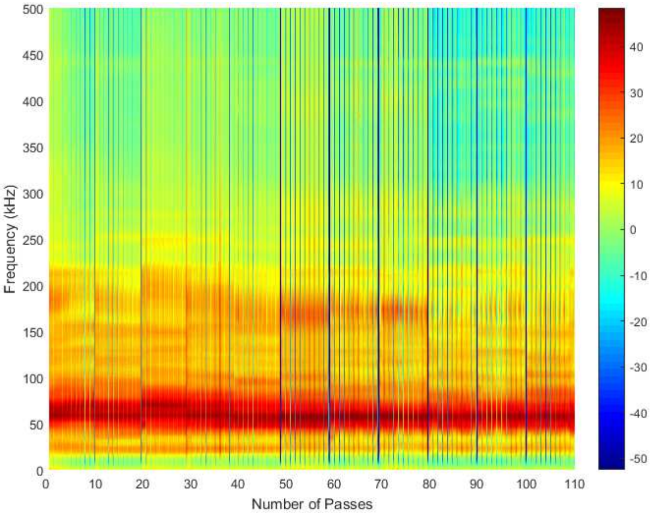


Figure 3.4: Spectrogram of the AE signal

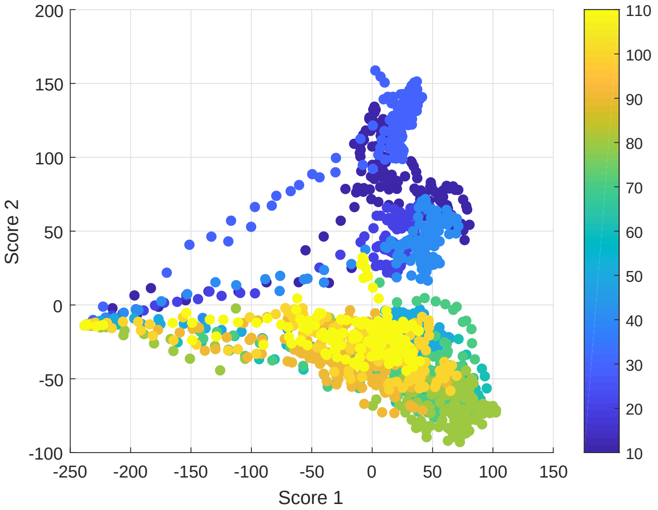
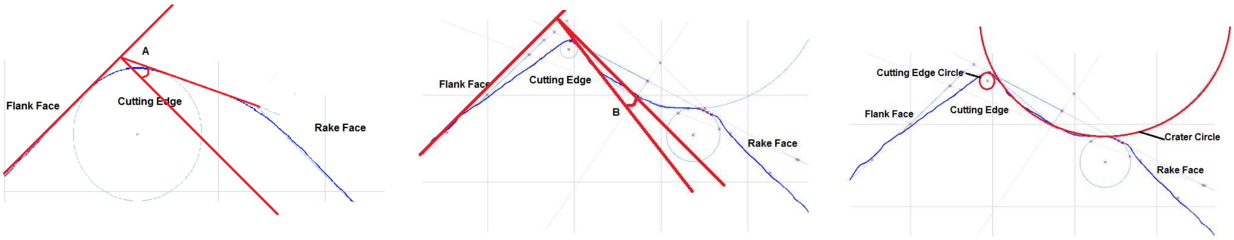


Figure 3.5: PCA of the frequencies

The frequency with the highest power ($F_{highest}$) lies at 58.59 kHz. Given the saw tooth chip formation, it is plausible to assume the $F_{highest}$ frequency corresponds to shear deformation of the workpiece. For a new tool, a second peak of high power can be seen up to pass 40. This could be due to the transition stage of the cutting edge where the chamfer with a negative rake angle A (Figure 3.6a) is completely worn and the cumulation of crater and flank wear produces a sharp cutting edge with a positive rake angle B (Figure 3.6b). Moreover, these passes are also clearly separable from others by eye in the PCA graph. Consequently, this suggests that PCA of AE signals in the frequency domain can be used for classification of wear states for PCBN tools.



(a) (b) (c)

Figure 3.6: Profile of a (a) new tool (b) worn tool (c) worn tool with circles highlighted.

The $F_{highest}$ frequency is most powerful during the middle of the tool life, owing to the sharpness of the tool. The sharpness of the tool has been calculated here as a ratio of crater radius and cutting edge radius (Figure 3.7). These radii were found by examining the cutting edge circle and crater circle as seen in Figure 3.6c.

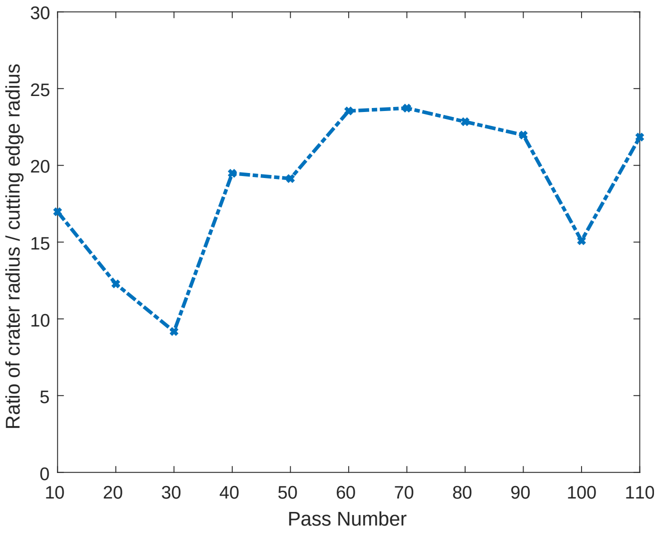


Figure 3.7: Sharpness of tool over time.

The frequency which is exactly 3 times the $F_{highest}$ (58.59 kHz) at 175.77 kHz, has a high amplitude, and is present in the middle of tool life and dissipates, though it does not completely disappear. Traces of it can be seen during passes 100 to 110. It could be assumed that this frequency component is caused by the collision of the tool with the chip and/ or the chip curl. This is on the grounds that the rate of curl depends on the segmentation frequency (the frequency at which the saw tooth behaviour occur - the $F_{highest}$ frequency in this case). The curling of a chip can occur naturally or as a result of force being applied to the chip [25]. The curling in this case is a product of crater wear which changes the rake face and produces a surface for the chip to collide against [26]. In the trial, it was seen that during the middle section of the tool′s life, it has very little ability to clear swarf from the cutting zone. The swarf is tangled and gathers around the cutting zone. This is because the crater wear is deep and the chamfer which directs the chips away (Figure 3.6a) from the cutting edge is almost non-existent (Figure 3.6b). It was witnessed that at this point, the chip does not break away hence affecting the number of tool - chip collisions as well.

4 Conclusions

Due to the challenges of measuring tools directly, machining outputs such as AE can be used as indirect measurements of tool wear. It is possible to use these indirect measurements with machine learning algorithms to automate the tool wear measurement process. Spectral analysis of AE signals collected during a face turning operation was carried out in order to understand whether acoustic emission from machining can be used as an indirect measurement of tool wear of PCBN inserts.

It was found that, the variation of the frequency component of the AE signals with the highest power is caused by tool wear, as all other machining conditions are kept constant. This frequency component is assumed to be due to shear deformation of the workpiece to produce a chip. This will be examined further in a future study by collecting chips and also by analysing force in the frequency domain. The sharpness of the tool affects the magnitude of the frequency band with the highest power significantly.

The change in tool profile from a negative rake angle to a positive rake angle is thought to correspond to two frequencies with similar high amplitudes at the start of tool life. The clusters found in the PCA results corresponding to these early passes can be easily separable from the rest by eye.

Curling of chips at the tool cutting edge may be responsible for a frequency band with high amplitude at three times the frequency with the largest power. This needs to be investigated further by studying chip segmentation frequency through force data and also by collecting chips during machining. If this is a non-linear effect, it could provide more information about the machining process and subsequently, the tool wear state.

These findings suggests that AE can be used as an indirect measurement of tool wear for PCBN inserts. The results from the principle component analysis conducted on the spectral information of the AE signal can be fed through classification algorithms as the next step of automating tool wear measurements.

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