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Analysis of audible sound energy emissions during single point machining across full tool life.

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In precision engineering, tool wear affects the dimensional accuracy and surface finish of machined components. Currently, errors associated with tool wear remain uncompensated for and are usually only detected at the end of the machine cycle, by which time the product may be scrap. If real-time, accurate monitoring were available, machine parameters could be adjusted to compensate for tool wear thereby minimising waste. Experienced machinists in Schivo Precision have been able to detect a poorly performing cutting operation through the sound emitted from the machining centre during the various phases of the cutting cycle and, although not a precise science, appear capable of informally differentiating between a good process and a degraded one. In this article experimental work was undertaken on a single point machining operation whereby the sound energy emissions from the machine were logged and analysed for the full life of the tools. The experiments demonstrated consistent acoustic signatures, which are specific to the tool in a known good cutting state, and distinct, but also consistent sound energy signatures, in a known bad cutting state. The experimental measurements replicated the audible range of human hearing and sought to determine what encouraged experienced machinists to declare a machining process to be in a state of degradation.

Keywords: Computer numerical control (CNC) machining, process monitoring, cutting tool degradation, sound energy process monitoring, Acoustic Emissions. Cutting tool performance.

1. Introduction

For many years an effective methodology for the real-time monitoring of the performance of cutting operations in manufacturing has been sought. Currently the only true method whereby the effectiveness of a material removal process can be evaluated is through inspection of the resultant workpiece at the end of the manufacturing cycle, by which time any performance shortfall cannot be corrected and the product may be considered scrap. Teti. *et al* [1] provided an overview in 2010 of the state of the art of the many methodologies that continue to be examined as a viable means of monitoring tool wear in CNC machining.

The fact that similar reviews were undertaken previously in 1995 by Byrne *et al*[2] in 1988 by Tonshoff *et al* [3] in 1983 by Tlusty & Andrews [4], and in 1976 by Micheletti *et al* [5] provides a measure of the desire that continues to exist to develop a technology for live feedback of tool cutting performance.

Through the range of research various approaches have been, and continue to be, explored in the expectation that one element; or a combination of elements; inputting to or outputting from the CNC cutting process will provide the valuable information on the performance of the cutting interface.

The process variables that have been examined include motor power and currents, machine vibrations, temperature, force and torque analysis, ultrasonic evaluation, workpiece irradiation and acoustic emissions. The research outlined in this paper examines the viability of audible sound emissions as a standalone process-defining variable. The frequency range of this analysis will be the spectrum of human hearing, which is 0 to 20 kHz, at a maximum. The decision to examine this frequency range is to test the premise that experienced machine operators can "hear" a machining process degrade.

Currently there are a number of projects on a multi-industry manufacturing scale, investigating the potentials for live monitoring of the performance of the material removal/cutting operations within modern precision manufacturing.

The ADACOM [6] project is established with the intent of providing adaptive control of the metal cutting process. This project is currently working on researching a modular platform to allow the metal cutting process to self-adapt to changes in performance.

The IFaCOM [7] project has been working on intelligent fault correction and self-optimising systems and the aim of this project is to develop the type of manufacturing process monitoring that is now desired within modern manufacturing operations to allow control of the operation at a level of assurance that previously could only be attained through intensive product inspection after manufacture. This research is investigating the usefulness of sensoring in the monitoring of high precision processes.

The SOMMACT [8] project is researching the use of Coordinate Measuring Machine (CMM) touch trigger probes to evaluate and inspect the resultant workpiece from the manufacturing operation as an element of this operation. The project proposes that the information from the final automated inspection of the workpiece will allow this information to teach the system to better inspect the resultant work pieces. This proposal is worthwhile, however it would be of more worth to evaluate during the process rather than evaluate the success of the process based on the resultant output.

This requires intensive knowledge of various process conditions, and the experimentation that will be further outlined in this paper aims to add to the research and the industrial communities understanding of these dynamics.

One of the earlier large industry-led projects was by Lazarus [9] where a correlation was determined between the state of tool wear and the level of acoustic emissions (AE) and audible sound energy from the process. The project was sponsored by Allied Signal Aerospace in conjunction with the US Department of Energy. The findings, although not equipped with the technology available today, concluded that the concept was fundamentally sound.

Otman & Jemielniak [10] examined catastrophic tool failure (CTF) and concluded that the AE bursts detected during the experimentation may not be reliable measures of catastrophic tool failures. Among other research into the use of AE to predict CTF, there is evidence to support the premise that ongoing continuous monitoring of the process will pre-empt catastrophic failure, such as outlined by Holroyd [11].

Some examples of investigations into the use of acoustic emissions to determine the status of processes and structures include, but are not limited to, Al-Ghamd & Mba [12], where the use of acoustics, combined with vibration analysis, was shown to be beneficial in the identification and estimation of defect size in bearings. Augereau *et al* [13] examined the use of acoustics to determine damage levels in stainless steel (304L SS) subjected to various treatments. A similar study was undertaken by Kim *et al* [14] into the development of an on-line tool-life monitoring system using acoustic emission signals in the shaping of gears.

A general study undertaken by Dolinšek & Kopač [15] into the general acoustic emissions of a variety of tool configurations and analysed the relationship between the degree of wear observed on the tool under a scanning electron microscope (SEM) and the observed energy of the acoustic emissions. The research concluded that the energy of the acoustic emissions was affected by the degree of observed tool wear, and also that this varied based on the composition of the cutting insert. Govekar *et al* [16] analysed acoustic emission signals and the monitoring of machining processes and concluded that valuable information about the performance of the process can be gleaned from a correctly specified sensor configuration, a conclusion also reached by Tonshoff *et al* [17].

A number of detailed studies have been undertaken to determine the worth of the acoustic emission signal from a specific machining operation. The theoretical effectiveness of AE has been examined for fracture detection by Rao [18], in drilling by Gomez *et al* [19], in turning by Li [20] and Reddy [21] and in micro-milling by Jemielniak & Arrazola [22].

A large body of research has been undertaken into associated signal pre- and post-conditioning methodologies by Jemielniak [23], Wilkinson & Reuben [24], who examined tool wear prediction using multiple sensors and artificial neural networks. With current and recent advances in computer analysis technologies, notably the development of neural network technologies as discussed in detail by Teti *et al* [1] there is much focus on the analysis of the data that is offered by the machining process from the sensor configurations. Much of the recent research focus has tended towards examination of what to do with the raw signal data from various sensors.

This paper examines the possibility that some experienced machinists are indeed capable of discerning between a good and a degraded machining process through variations in the audible sound emissions from the process. A flowchart comparison is presented in Figure 1.

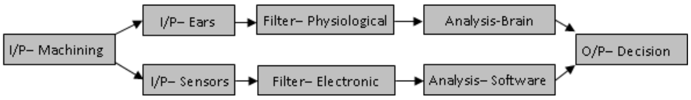

Figure 1. The process flow.

There is extensive evidence in the literature [25,26,27,28] that the input to the process described in Figure 1, which is the machining operation, is understood.

With a few exceptions, such as Rubio and Teti [29,30], investigation into acoustic emissions of the machining process has focussed on the frequency range of greater than 20kHz, outside the general range of human hearing. The International Standards Organisation (ISO) defined [31] range of acoustic emissions allows for the frequency range of 20 kHz to 100 kHz for the purposes of machine monitoring, which is beyond the range for human interpretation that is the subject of this paper.

2. Experimental outline

The fundamental aim of this work is to determine if it is possible to determine through simple audio sensor monitoring the difference in audible acoustic emissions, between a tool cutting a material in a state of cutting edge integrity and a tool in a worn state.

2.1. Experimental setup

The cutting configuration employed was single point cutting in a facing operation on a CNC lathe.

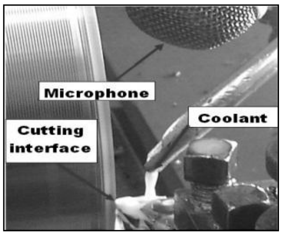

Figure2. Setup

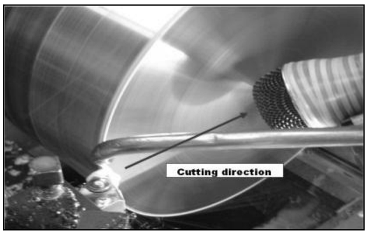

Figure3. Direction of cutting

Figures 2 & 3 detail the actual experimental setup, location of microphone in relation to cutting interface and tool holding configuration. The machining operational parameters are shown in Table 1:

CNC Machine used	Harrison VM500 Lathe
Workpiece material	High speed tool steel
Cutting Tool	CNMG 120412 insert
Coolant	Hocut HO80
Feed (mm/sec)	120M/ Minute
Speed (rot ft./sec)	130 RPM
Cut depth	0.2mm

Table 1. Machining operational settings

The sound energy emissions were detected using an audio microphone connected to the soundcard of a Toshiba Satellite laptop and recorded for later analysis using an audio software package. The software and acoustic detection hardware configuration employed is detailed in Tables 2 & 3.

Software package	Audacity [32]
PC	Toshiba Satellite
Soundcard	Conexant high definition
Operating system	Windows XP
Microphone	Shure SM58

Table 2. Sensor settings

Input channels	2 (stereo) input
Sampling rate	44100 kHz
Filtering	Hanning Window

Table 3. Data acquisition settings

2.2. Experimental methodology

The machining configuration and settings described above were used to machine material continuously, while recording the resultant microphone pickup on the PC. By repeatedly using a single point turning configuration the experiment is monitoring only the interaction of the same cutting edge type on the same material type.

While the experiment took place on Schivo's machine floor, for the duration of the experiment there were no other machining operations taking place in the vicinity, which might have added interfering acoustic components and compromise the signals being detected. To further confirm that any background acoustic energy was negligible to the sensor acquisition the monitoring equipment was set to record background noise at the beginning and end of the experiment and spectra were taken for these signals to confirm that their effect would be negligible.

The experiment was run twice back to back with identical settings and configurations. For each experimental cycle the only change was the replacement of the cutting tool insert with an identical unit. During the experiment the surface finish being obtained from the cutting operation was monitored with a Mahr PocketSurf portable surface roughness meter. The surface tester was used to monitor the value of R_A (roughness average) across the machined surface. R_A was selected over R_{max} or R_Z as this value is not as susceptible to skewing due to anomalous area detection during the measurement. The stroke length of the surface tester probe was set to 5mm and the readings were taken from the material *in situ* on the machine, to avoid disruption to the set-up.

Two full experimental cycles were undertaken facing the billet, removing 0.2mm of material for each pass. At the end of the experimental cycles two full sets of acoustic emission data were available. The total lengths of the two recordings are given in Table 4.

Cycle	Duration
Recording cycle 1, insert 1	1 hour, 33min, 42 seconds
Recording cycle 2, insert 2	1 hour, 29min, 10 seconds

Table 4. Data sets recorded during experimentation

The recorded signals were stored on an external hard drive for later analysis. Both cutting inserts were marked up and retained.

The analysis of this data will consider the following questions:

(1) Is there a perceptible variation between the acoustic emission data from known good tool cutting conditions and the emission data where it is known that the tool is not cutting efficiently?
(2) Are there demonstrable correlations across a number of samples of acoustic emission spectra, across the range of the same tool cutting cycle, where the tool is known to be cutting effectively?
(3) Are there demonstrable correlations across a number of samples of acoustic emission spectra across the range where the tool is known to be worn and not cutting desirably?
(4) Is the data from the two experiments substantially similar, i.e. are the emission spectra for known good and known bad on both experimental cycles comparable in content?

It was determined to divide the cutting cycle into three phases of tool operation across the tools life. .

Phase 1 is where the insert is cutting at optimum efficacy, due to the fact that since manufacture the tool cutting interface has experienced no torsional stresses and has not been exposed to plastic deformation. This optimum phase is expected to last no longer than one or two cutting passes. However, 20 passes were allowed during the analysis to allow for tool "wear-in" and thermal deformation.

Phase 2 is where the cutting insert is experiencing normal operation. This is expected to be the longest, and naturally the most consistent in terms of performance, efficiency, temperature and audible acoustic emission.

Phase 3 is where the cutting edge and supporting material of the insert is beginning to exhibit wear characteristics. The differences between the second and third phases of the insert's operation and audible acoustic emissions that are released during these phases are those that are of interest to this research.

3. Results

As outlined, measurements of the surface finish of the workpiece were taken regularly during the experimental cycles to evaluate the performance of the cutting operation. Table 5 illustrates the timing where the samples were taken from each of the two experimental data sets, the performance of the cutting interface in terms of the machined finish in R_A and how these relate to the expected phases of cutting performance.

Phase	Experimental trial 1		Experimental trial 2	
	Sample Start	R_A	Sample Start	R_A
Phase 1	60 sec	17μM	70 sec	22μM
	115 sec	24μM	150 sec	22μM
Phase 2	530 sec	22μM	600 sec	26μM
	740 sec	23μM	720 sec	27μM
	2140 sec	27μM	2165 sec	27μM
	3180 sec	48μM	3190 sec	36μM
Phase 3	4340 sec	59μM	4400 sec	50μM
	4430 sec	84μM	4460 sec	72μM
	4500 sec	102μM	4540 sec	98μM

Table 5. Acoustic samples and detected finish

Samples of 10 seconds duration were taken from the audio data for both experimental trials. The sample time of 10 seconds was chosen to favour consistently occurring emissions, over extraneous emissions, on the premise that the experienced operators are coming to their conclusions in a similar manner. Across the full audio sample, two sets of samples were taken in phase 1 (new, perfect cutting), four across phase 2 (standard cutting) and three across phase three (worn cutting). The timings of the sample clipping are shown in Table 6. In this table there is also a descriptor for the sample. An explanation of the descriptor's notation is given in Table 7, which will be used in the later analysis of these results.

Phase	Trial 1		Trial 2		Ident
	Time (sec)	Desc	Time (sec)	Desc	No
Ph 1	47-57	T1SRT1	53-63	T2SRT1	1
	110-120	T1SRT2	130-140	T2SRT2	2
Ph 2	518-528	T1STD1	572-582	T2STD1	3
	713-723	T1STD2	699-702	T2STD2	4
	2119-2129	T1STD3	2143-2153	T2STD3	5
	3159-3169	T1STD4	3166-3176	T2STD4	6
Ph 3	4312-4322	T1WRN1	4374-4384	T2WRN1	7
	4415-4425	T1WRN2	4438-4448	T2WRN2	8
	4476-4486	T1WRN3	4518-4528	T2WRN3	9

Table 6. Comparison samples and descriptions for comparisons

Descriptor	Explanation	Ident
T1SRT1	**Trial 1, Start sample 1**	**1**
T1SRT2	**Trial 1, Start sample2**	**2**
T1STD1,2,3,4	**Trial 1, Standard cutting 1 etc.**	**3,4,5,6**
T1WRN1,2,3	**Trial 1, Worn cutting 1 etc.**	**7,8,9**

Table 7. Sample descriptor explanations from table 6

The plotted frequency spectrum was divided into 255 individual frequencies, to allow for a granular examination of the data.

A plot of the frequency response across the nine sample sets in trial 1 is presented in Figure 4.

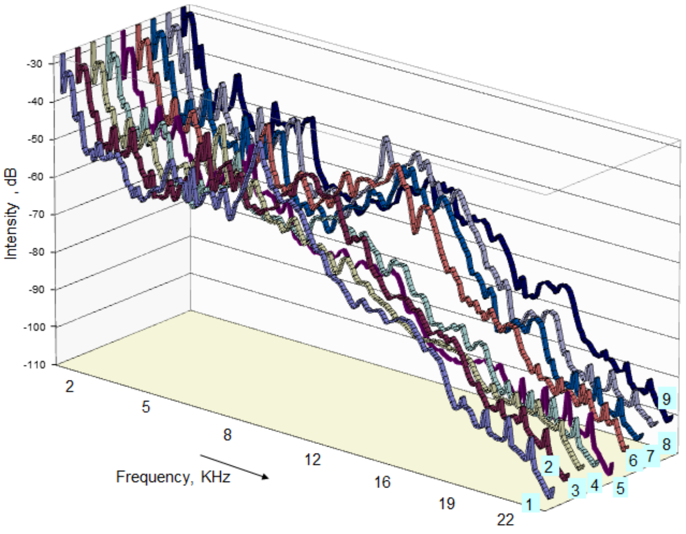

Figure4. Full acoustic spectrum of trial 1, 9 sample sets across three machining phases

Figure 5 shows the corresponding dataset for trial 2, again with the full frequency response for the nine samples graphed. Note that the x-axis for both Figures 6 & 7 starts at 80Hz and ends at 22 kHz.

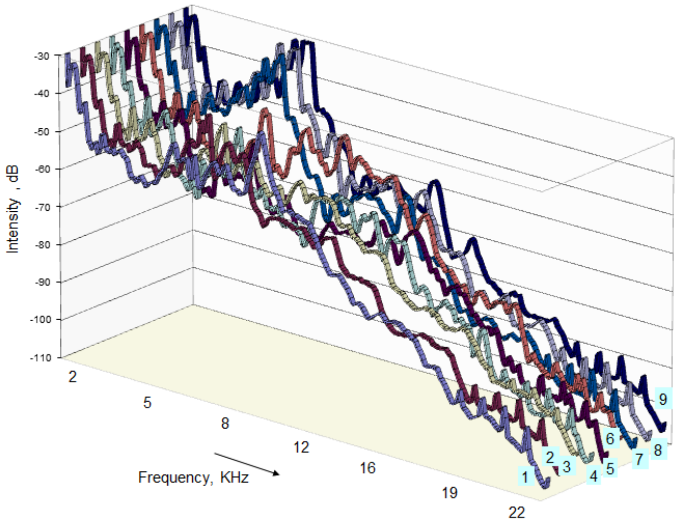

Figure5. Full acoustic spectrum of trial 2, 9 sample sets across three machining phases

It is clear from the spectra in Figures 6 & 7 that the differences in the frequency response between the phases of machining are more evident within the mid-region of the frequency analysis, in the 8-16kHz range, as can also be seen in the spectra themselves, in Figures 4 and 5.

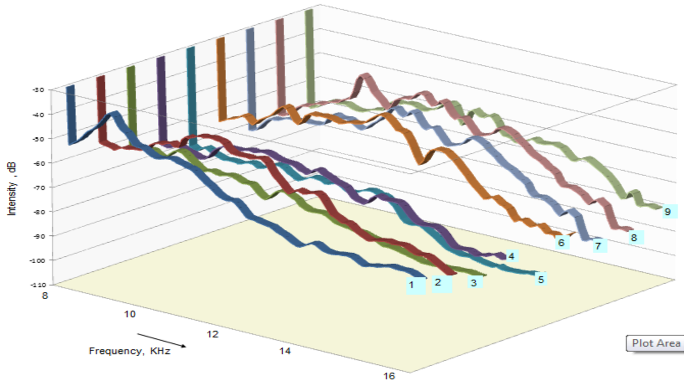

Figure6. Acoustic spectrum of trial 1, 9 sample sets across three machining phases. Frequency range 8-16 kHz examined.

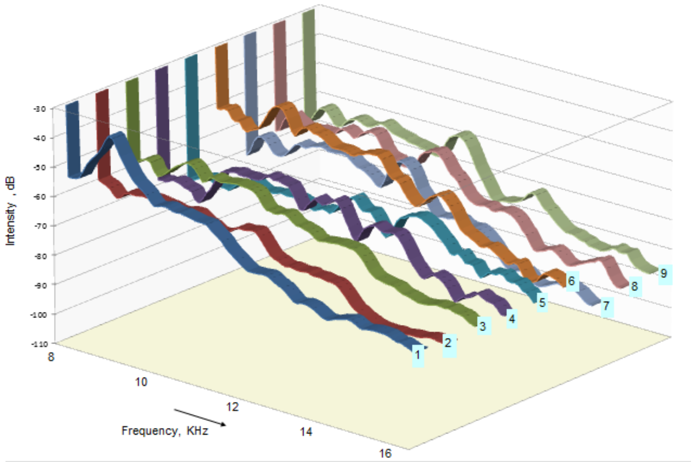

Figure7. Acoustic spectrum of trial 2, 9 sample sets across three machining phases. Frequency range 8-16 kHz examined.

Table 5 gave details of the workpiece surface finish, which in turn provides information on the performance of the cutting interface. It is therefore possible to graphically illustrate the surface quality against the evaluation time points for both trials. This is shown in Figures 8 & 9. As can be seen in these figures, the quality of the cutting operation deteriorated generally around the same time during both trials. However the dynamics of the deterioration of performance for both inserts was different.

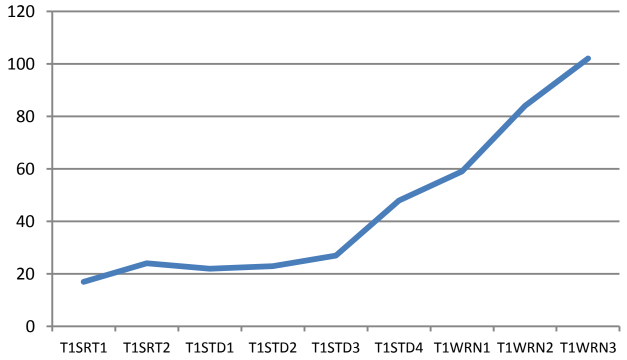

Figure 8. Graphical representation of the surface quality of the workpiece across the full range of tool life- Sample 1. Surface roughness R_a (Y)

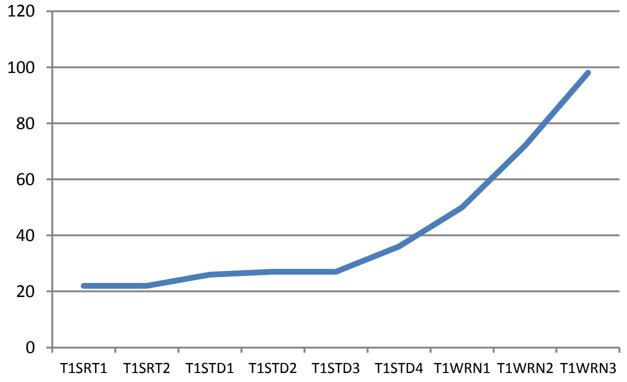

Figure 9. Graphical representation of the surface quality of the workpiece across the full range of tool life- Sample 2. Surface roughness R_a (Y)

4. Discussion of results.

A simple aggregate spectral difference approach has been applied to analyse frequency spectrum variations, by calculating the cumulative frequency domain amplitude differences between the start spectra and subsequent sample spectra. This is a simple analysis of audible emission variations during the tool life time. These spectral variations can be compared to the state of the cutting interface, or the degree of wear and structural deformation of the tool. The underlying premise in this technique is that human operators notice the *change* in audible emission spectra between normal and end of tool life. This comparison is plotted in the following graphs, initially over the full measured spectral range (0-22kHz in Figures 10 & 11) and in the latter two graphs in the more promising narrower spectral range (8-16 kHz in Figures 12 & 13).

Note that the spectral comparisons are relative to the first standard reading, respectively T1STD1 or T2STD1 just after 500 seconds of operation. This is Point 1 in Figures 10 – 13. Points 2-7 are the comparisons of subsequent Standard (2-4) and Worn (5-7) measured data.

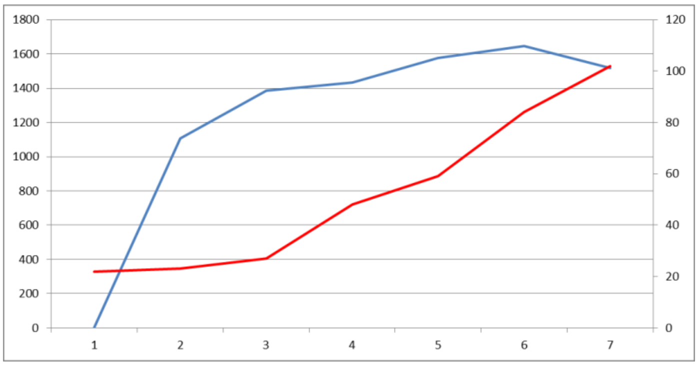

Figure 10. Spectral differences for samples against T1STD1 (Blue) and cutting performance measured Ra (Red) full spectra (0-22kHz)

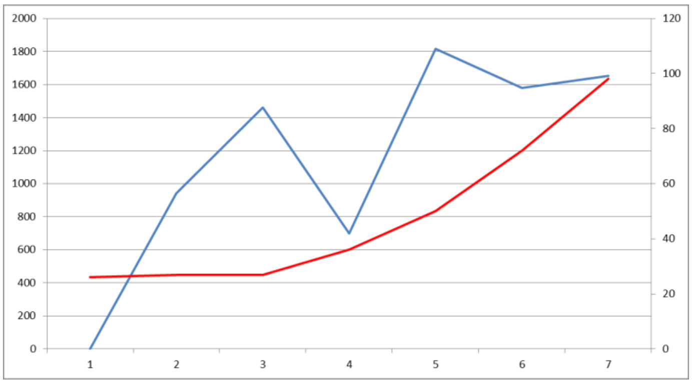

Figure 11. Spectral differences for samples against T2STD1 (Blue) and cutting performance measured Ra (Red) full spectra (0-22kHz)

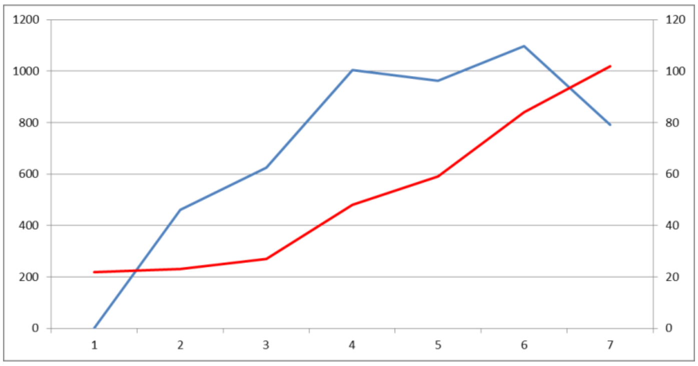

Figure 12. Spectral differences for samples against T1STD1 (Blue) and cutting performance measured Ra (Red) - narrowed spectra (8-16kHz)

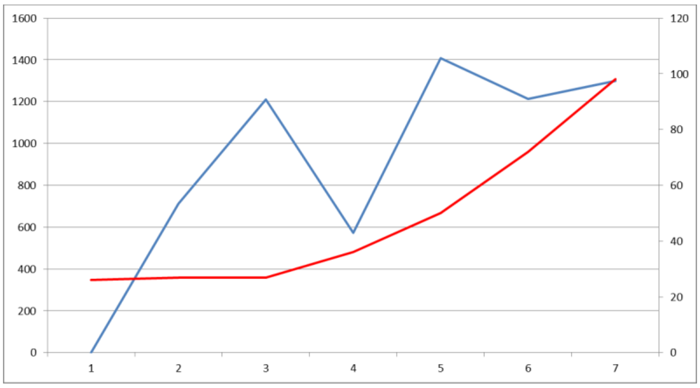

Figure 13. Spectral differences for samples against T2STD1 (Blue) and cutting performance measured Ra (Red)- narrowed spectra (8-16kHz)

The spectral analysis showing the spectral variation over the tool life in Figures 4 & 5 supported the belief that experienced machinists can detect the differences between adequately performing cutting operations and audible acoustic emissions from a poorly performing process, as there seems to be an increase in sound energy over certain frequencies as the tool progresses through its life. The data collected during the experimental runs appeared to indicate during initial visual analysis (Figures 4 & 5) that the spectra demonstrated differences for each of the identified machining phases.

Further analysis of the spectral data against the cutting performance of the insert is shown in Figures 10 to 13. The tool wear spectra curves do seem to rise with the detected degradation of the cutting interface (as represented by the measured finish of the work piece). As the work piece was not removed from the machine during the experiment, and no other breakdown or interference was undertaken during the experiments, the only process parameter that could affect the surface finish is the performance of the cutting interface, and it is reasonable to assume that this is the single contributor to this.

While the graphs do show an increase in audible acoustic emission differences, even when the measured finish is acceptable, this increase continues even further when the measured finish is no longer acceptable. As most change appeared to occur between 8kHz and 16kHz, Figures 12 and 13 display the aggregate spectral for each of the phases with respect to the first standard phase figure.

As outlined in the review of the literature in section 1 above, traditional studies into the use of acoustic emissions in machining have focussed on the non-audible range of acoustics, in the 20 kHz to 100 kHz range, as defined in ISO/DIS22096 [31]. The literature has, because of this definition, focussed less on the audible emissions with the exceptions [29,30] as mentioned. The results outlined in this paper provide merit to this belief, although there is certainly, from both the literature and additional sensor information retrieved from machining centres in terms of vibration and acoustic emissions in the non-audible range evidence that information from more than one sensor configuration is likely the key to effective evaluation of the cutting interface performance.

5. Conclusions

Four questions were posed in section 2.2, these are addressed thus:

(1) For this work there was a perceptible variation between the audible acoustic emission data from known good tool cutting conditions and the emission data where it is known that the tool is not cutting efficiently. This is illustrated across all the presented graphs, showing that there is a marked variation in the detected emissions as the cutting performance of the tool degrades, as measured by the resultant surface finish.

(2) There are some demonstrable correlations across the range of the same tool cutting cycle, where the tool is known to be cutting effectively, this can be seen in the comparison from sample 1 to sample 2 where the resultant spectra is observed to follow similar trends.

(3) There may be some further correlations across a number of samples of audible acoustic emission spectra across the range where the tool is known to be worn and not cutting desirably. This aspect requires further investigation.

(4) The data from the two experiments are broadly similar. The relationship between the degradation of the cutting performance and the trend of the sound energy changes is notably similar across both samples. Although, for sample two, illustrated in Figure 11, there is an unexplainable dip in acoustic energy variation detected at identifier point 4, broadly the trend lines are the same across both trials.

The experimentation outlined in this paper, and the results contained within, lead to the following four conclusions.

- Examination of the audible acoustic spectra highlights the possibility of identifying discrete phases of the cutting interface performance. The wear could possibly be divided into new cutting, optimal cutting, and degraded cutting, and the differences were most pronounced around the areas of the tool cycle where there was a cutting phase shift.
- The analysis also showed that the audible acoustic emissions from the cutting interface begin to change in advance of the physical manifestation of the tool wear condition. Perhaps then emissions can be used to indicate change before the actual cutting performance is degraded to a point that is negatively affecting the resultant workpiece condition.
- The data suggests that where the acoustic emissions within the range of human hearing are being analysed, while the range may be further reduced (as here reduced to 8-16kHz) the additional insight gained may not be sufficient to justify narrowing the range- *in this application of cutter & material.* This may very well only relate where the techniques applied in this paper are applied. This is worth investigating in further research.

6. Further investigation.

This research as outlined above was triggered by the anecdotal evidence that experienced machine operators can evaluate the performance of the cutting operation though their interpretation of what they can hear. This has, in industry been largely found to be a reasonably accurate measure, with predictive tooling changes made on this basis.

Evaluation into the audible response capabilities of experienced machinists who have been found capable of discerning between good and poor machine operations is worth investigating, in the context of the evidence presented in this research.

This paper, as presented, is part of a larger research project to investigate the potential use of sound energy, vibration and acoustic emissions in the CNC machining operation. From the results presented above it can be concluded that there are repeatable acoustic signatures within both know good cutting conditions and during a known worn tool cutting condition.

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