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Influence of Cutting Parameters and Tool Wear on Acoustic Emission Signal in High-speed Turning of Ti-6Al-4V Alloy

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Abstract

Titanium and its alloys are an important group of engineering materials, with a wide range of applications in aerospace, aircraft, automotive, chemical and biomedical industries. They have excellent combination of strength and fracture toughness as well as low density and excellent corrosion resistance but with poor machinability due to their low thermal conductivity and high chemical reactivity with cutting tool materials. In this study, the effects of cutting parameters and tool wear on the Acoustic Emission (AE) signal in high-speed turning of Ti-6Al-4V alloy with new generation of cemented carbide tools was investigated. Machining trials were conducted at different cutting conditions, the AE signals were acquired and the signal features in the time-domain (mean, standard deviation, amplitude, root mean square, skewness, and kurtosis) and signal features in the frequency-domain (frequency and amplitude) were extracted. The essence of this study was to identifying the features of AE signal capable of being used as potential process indicator for development of automated monitoring and control system for turning of Ti-6Al-4V alloy. The results demonstrated AE signals as potential indicator for Tool Condition Monitoring (TCM) in turning of titanium Ti-6Al-4V alloy.

Keywords: titanium Ti-6Al-4V alloy; acoustic emission; turning; tool wear, tool condition monitoring.

INTRODUCTION

Titanium and its alloys are an important group of new generation of engineering materials. They are used widely in aerospace, aircraft, automotive, chemical and biomedical industries, due to their excellent combination of strength and fracture toughness as well as low density and excellent corrosion resistance that are maintained at elevated temperature conditions (Ezugwu and Wang, 1997). Different machine components ranging from simple to complex configurations made of titanium and its alloys are produced by conventional machining processes such as: turning, milling, drilling, boring etc. However, despite the wide range applications of titanium and its alloys, they present poor machinability due to their low thermal conductivity and high chemical reactivity with cutting tool materials, leading to adverse condition at the cutting edge at elevated temperature and rapid tool wear. Therefore, titanium and its alloys are classified in the group of difficult-to-cut materials and the need for economic machining of titanium and its alloys has been the concern of many researchers. Previous studies on the machining of titanium and its alloys have described the chip formation mechanism and its control, tool materials and wear mechanisms (Ezugwu and Wang, 1997; Komanduri and Von Turkovich, 1981; Barry et al., 2001; Ezugwu, et al 2003). In recent times, research interest on the development of appropriate monitoring systems for tool wear in cutting of titanium and its alloys is becoming increasingly popular. Most the condition monitoring techniques employ force, spindle motor torque, current or power, acoustic emission signals, etc., or a combination of these signals. Of all these monitoring indicators, AE signal is one of the most applied. Kannatey-Asibu Jr. and Dornfeld (1982) has defined AE as the transient elastic energy spontaneously released in materials undergoing, deformation, fracture or both. The possible sources of AE during metal cutting processes has been reported as: plastic deformation in the primary shear zone; chip sliding on the tool rake face; tool flank-workpiece rubbing; chip breakage (during the formation of segmented or discontinuous chips); collisions between chip and tool and macro fracture of the cutting tool (Kannatey-Asibu Jr and Dornfeld, 1982; Diniz, et al 1992; Tönshoff, et al 2000; Li, 2002; Chungchoo and Saini, 2002).

AE signal has also been used as indicator for monitoring the cutting operations of different engineering materials. AE energy when machining steel increased with the cutting time and tool wear (Haber, et al. 2004). Tönshoff *et al.* (2000), after machining hardened steel (16MnCr5 with 60 - 62 HRC), with a fresh tool edge reported that high AE amplitudes were generated with lower damping rate effect on the tool-workpiece system. They also observed that the damping effect increased with flank wear and consequently the AE energy level decreased. Hence, the AE amplitude increased with tool wear.

Also Lemaster *et al.* (1985) has reported that AE energy levels decreased with cutting time and tool wear during wood turning. The possible reason for this behaviour was due to a change in the chip formation process. They showed that the chip produced when machining with a sharp tool were short discontinuous and changed to long continuous chips when the tool was worn. They explained that in wood machining higher AE energy were generated as a result of the formation of segmented chips. Hence, continuous chip accounts, in part, to the reduction in AE energy as tool wear increased. Chung and Geddam (2003) has reported that the power spectrum of AE root-mean-square increased with cutting speed, feed rate, axial depth of cut, radial depth of cut and tool wear in end milling of AISI 4140 steel. Chiou and Liang (2000) has also applied the AE root-mean-square for monitoring of chatter vibration and tool wear conditions when turning of 6061-T6 aluminium alloy. Their study showed that the AE signal and vibration amplitude increased with flank wear. An empirical model relating AE root-mean-square peak with both tool fracture area and cutting force has been proposed by Diei and Dornfield (1987) and Fadare *et al.* (2010).. Blum and Inasaki (1990) has demonstrated that the modal value of AE amplitude distribution increased with flank wear. Recently, Andoh *et al.* (2007) has studied the effects of cutting speed, feed rate and depth of cut on acoustic emission's energy, amplitude, root-mean-square and frequency in drilling of composite laminates. Their study revealed that, cutting conditions have significant influence on AE signal, thus indicating the potentials of AE signal as viable monitoring indicator in metal cutting operations.

Table 1. Chemical composition (wt. %) of Ti-6Al-4V alloy

Chemical element	Al	V	Fe	O	C	H	N	Y	Ti
Min.	5.50	3.50	0.30	0.14	0.08	0.01	0.03	50ppm	Balance
Max.	6.75	4.50	-	0.23	-	-	-	-	-

Table 2: Mechanical properties of Ti-6Al-4V alloy

Tensile strength (MPa)	0.2% Proof stress (MPa)	Elongation (%)	Density ($g.cm^{-3}$)	Melting point (°C)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Measured Hardness* (HV_{100})
900-1160	830	8	4.50	1650	6.6	Min. = 341, Max. = 363

* Confidence interval (CI) of 99%, represented by the minimum (Min) and maximum (Max) values.

Table 3: Cutting conditions investigated

Cutting speed (v_c) m/min	10, 20, 40, 60, 90, 120 and 150
Feed rate (f) mm/rev	0.05, 0.1, 0.2, 0.3 and 0.4
Depth-of-cut (doc) mm	0.5, 1.0, 2.0, 3.0, 4.0 and 6.0

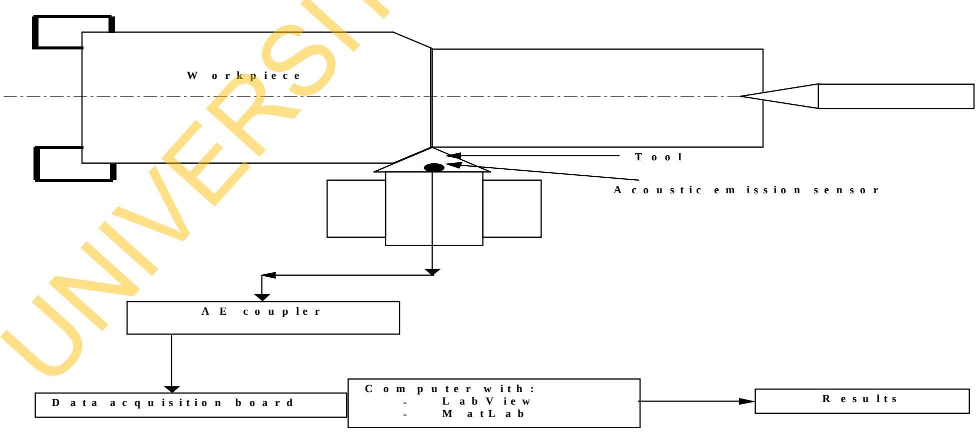


Fig. 1: Experimental setup of the machining trial

The AE sensor was fixed to the lower side of the tool holder close to the cutting edge with a bolt fixture. Silicon grease was used as coupling fluid between the sensor and the surface of the tool holder. The coupler has a low and high bandwidth passes of 50 and 200 kHz, respectively to filter spurious noise from the machinery and other mechanical processes unrelated to the cutting operation. The coupler was placed close to the sensor to minimize electromagnetic interference.

The AE signal strength was amplified to 40 dB level in the coupler. National Instruments data acquisition card (Model NI PCI/PXI-5112) with threshold frequency of 100 MHz and 2 acquisition channels with one trigger and LabView® signal processing software were used for automatic logging of the AE signals data. Preliminary machining trials were conducted at sampling rate of 1 MHz. It was observed that all events occurred below 300 kHz on the frequency domain. Therefore, the signals were captured at sample rate of 600 kHz. Ten thousand data points were recorded for each machining trial. Statistical parameters: mean, standard deviation, root-mean-square (rms), skewness, kurtosis and amplitude of the time series raw AE data and frequency and amplitude of the Fast Fourier Transform (FFT) were extracted from the AE signals.

All cutting trials were conducted with a fresh tool edge and each trial was repeated twice. Tool wear parameters: average (VB) and maximum (VBmax) flank wear and nose wear (VC) were measured with a Toolmaker travelling microscope connected to a digital readout device at a magnification of 25x

Data Processing and Analysis

The extracted signal parameters in the time-domain are defined as follows:

Mean (μ)

The mean of digitalised raw AE signal was estimated as:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (1)$$

Where N is number of digitalised points and x_i is individual signal for each time.

Standard Deviation (σ)

The standard deviation of digitalised raw AE signal was computed as given in Eqn. 2. This parameter quantifies the magnitude of the deviation from the mean value.

$$\sigma = \left(\frac{\sum (x_i - \mu)^2}{N}\right)^{1/2} \qquad (2)$$

Root Mean Square (RMS)

The root mean square (RMS) of the acquired raw AE signal was calculated as:

$$RMS = \left(\frac{1}{N}.\sum_{i=1}^{N} x_i^2.(i)\right)^{1/2} \qquad (3)$$

Skewness (Sk)

The skewness is the measure of the third central moment given in Eq. 4. The Skewness measures the symmetry of the function about its mean compared to normal distribution (Sk = 0). A negative skewness indicates a shift of the distribution to the left of the mean.

$$Sk = \frac{1}{\sigma^3}\int_{-\infty}^{\infty}(x_i - \mu)^3 . f(x).dx \cong \frac{1}{N.\sigma^3}\sum_{i=1}^{N}(x_i - \mu)^3 \qquad (4)$$

Kurtosis (Ku)

The kurtosis is the measure of the fourth central moment given by Eq. 5. The Kurtosis measures the flatness of the function about its mean compared to normal distribution (Ku = 3). Positive Kurtosis value implies a sharp distribution while negative implies flat characteristics.

$$Ku = \frac{1}{\sigma^4}\int_{-\infty}^{\infty}(x_i - \mu)^4 . f(x).dx \cong \frac{1}{N.\sigma^4}\sum_{i=1}^{N}(x_i - \mu)^4 \qquad (5)$$

Amplitude (A)

Amplitude shows the range of variation of signal intensity as given by Eq. (6).

$$A = x_{\max} + abs(x_{\min}) \qquad (6)$$

Where, x_{max} and x_{min} are the maximum and minimum values of the signal.

Fast Fourier Transform (FFT)

Spectral analysis was done to transform the acquired raw AE signal to frequency-domain using the Fast Fourier Transform (FFT). The extracted signal features in the frequency-domain were frequency and amplitude. According to Li (2002), an energy-signal f(t) can be decomposed into its Fourier Transform f(w), given by Eq. 7.

$$f(w) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(w).e^{iwt}.dt \qquad (6)$$

Where,

$$F(w) = \int_{-\infty}^{\infty} f(t).e^{-iwt}.dt \qquad (7)$$

f(t) and F(w) are known as the Fourier transforms pair.

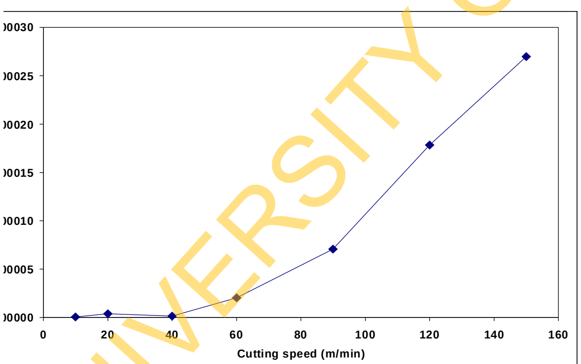
The Matlab® signal processing toolbox was used to perform the spectral analysis, and to calculate the statistical parameters.

RESULTS AND DISCUSSIONS

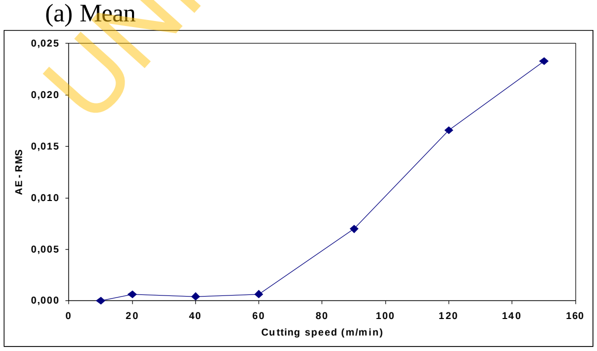
Influence of the cutting speed on AE signal

Figures 2(a-f) show the variations in the extracted signal parameters in both time- and frequency-domains (mean, rms, standard deviation, amplitude, skewness and kurtosis) for different cutting speeds ranging from 10 – 150 m/min at f = 0.1 mm/rev and doc = 0.5 mm. It can be observed that in Figures 2(a-d), the mean, RMS, standard deviation and amplitude of the signal increased with cutting speed. Increase in cutting speed led to higher material removal and deformations rates, consequently the amount of atomic conditions (e.g. dislocations and twinning, inter and trans-granular movements) responsible for plastic deformation mechanisms also increased as higher temperatures are generated at the cutting interface. It can also be seen in Figure 2(e) that skewness was positive for cutting speeds ranging from 10 - 85 m/min and negative for cutting speeds ranging from 85 - 120 m/min. However at 120 m/min the skewness was a typical normal distribution type (Sk = 0) and became negative again at cutting speeds higher than 120 m/min and above. The fact that Sk > 0 at low cutting speeds implied there was higher concentration of AE signal below the mean value (μ). Similar observation in AE signal has been reported in turning of mild steel (Chungchoo and Saini, 2002; Blum and Inasaki, 1990),

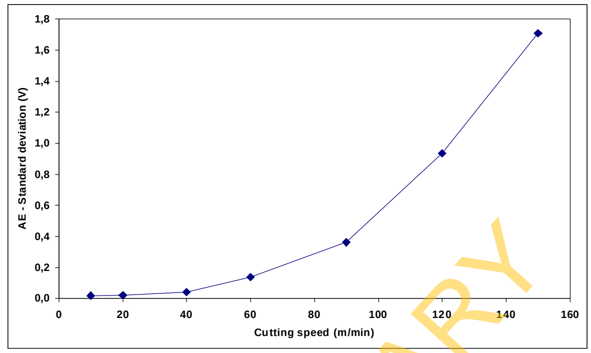
Figure 2(f) shows that the kurtosis of the signal was greater than 3 (Ku > 3) for all cutting speeds investigated. A normal distribution will have a Ku of 3. The Ku > 3 implied that high-peaked AE distribution was generated. It can also be observed that there was the tendency for Ku to shift closer to 3 when the cutting speed was increased above 150 m/min.



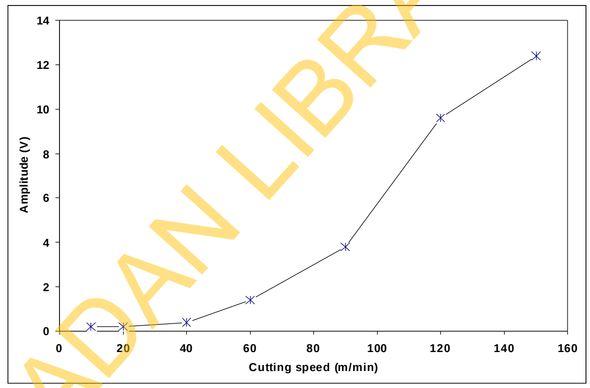
(a) Mean



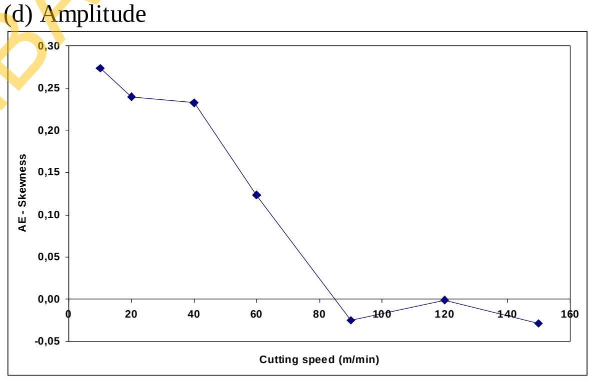
(b) RMS



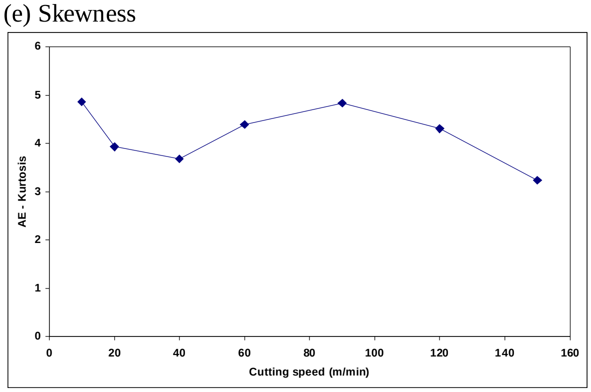
(c) Standard deviation



(d) Amplitude



(e) Skewness



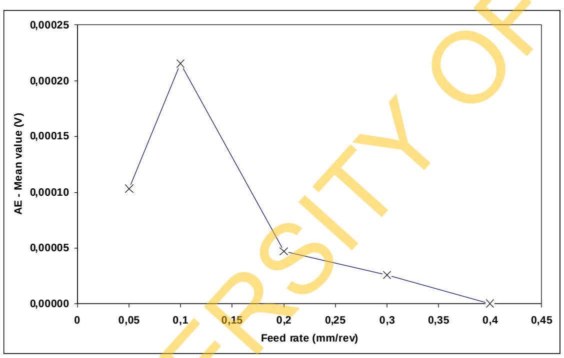
(f) Kurtosis

Fig. 2: Influence of the cutting speed on the AE parameters (f = 0.1 mm/rev and doc = 0.5 mm)

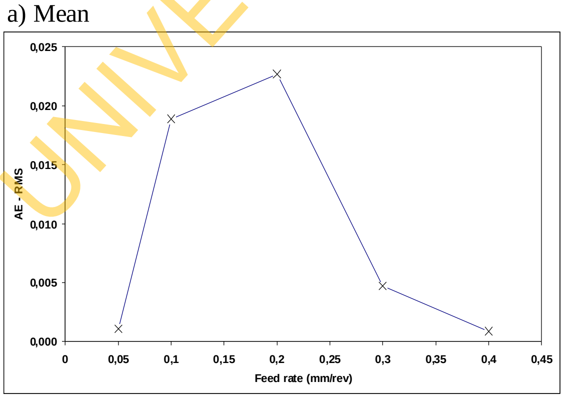
Influence of the Feed Rate on AE Signal

Figures 3(a-f) show the variations in the AE parameters (mean, RMS, standard deviation, amplitude, skewness and kurtosis) at different feed rates ranging from 0.05 – 0.4 mm/rev with cutting speed, v_c = 120 m/min and depth-of-cut, doc = 0.5 mm. Generally, Figures 3(b-d) show that increase in the feed rate up to 0.2 mm/rev led to increase in RMS, standard deviation and amplitude, followed by a reduction with further increase in feed rate. Trent and Wright (2000) reported that increase in feed rate increased the chip-tool interface temperature and corresponding enlargement of the chip-tool contact area. These two phenomena individually or together may contribute to the damping rate (Tonshoff et al 2000) and consequently a drop in the AE signal level when machining Ti-6Al-4V at feed rate above 0.3 mm/rev.

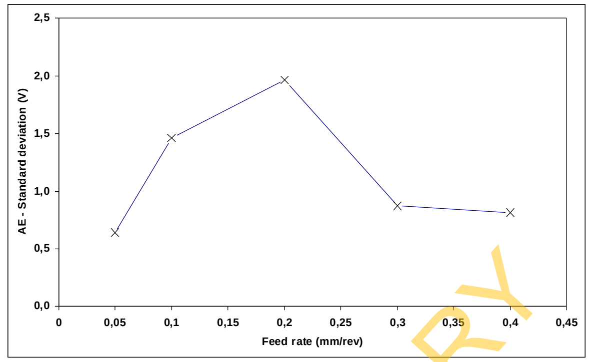
Figure 3(e) shows that the values of skewness were negative at the extreme feed rates of 0.05 and 4 mm/rev. For these cases there was predominance of the AE signal values higher than the mean value. There was a reverse in the behaviour at intermediate feed rates evaluated (0.1, 0.2 and 0.3 mm/rev) where the skewness values were positive. The kurtosis values during machining Ti-6Al-4V alloy (Figure 3(f)) was positive and greater than 3 in all feed rates evaluated. This behaviour implied a high-peaked AE signal distribution with large quantity of high amplitude signals.



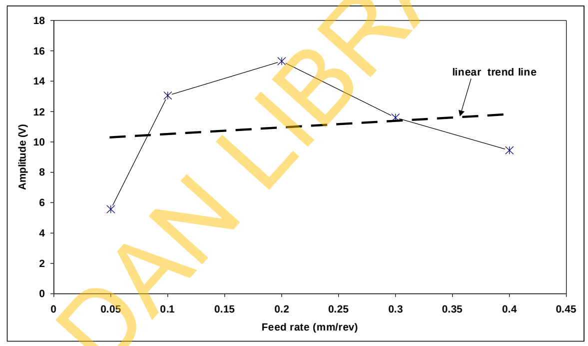
a) Mean



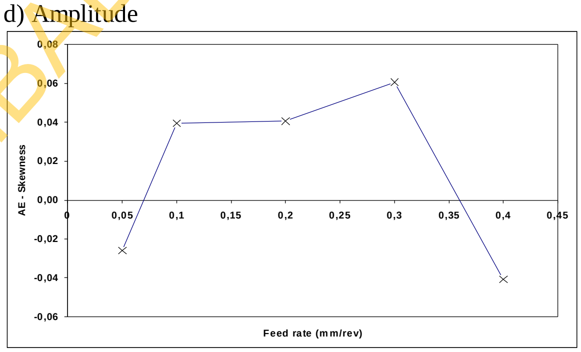
b) RMS



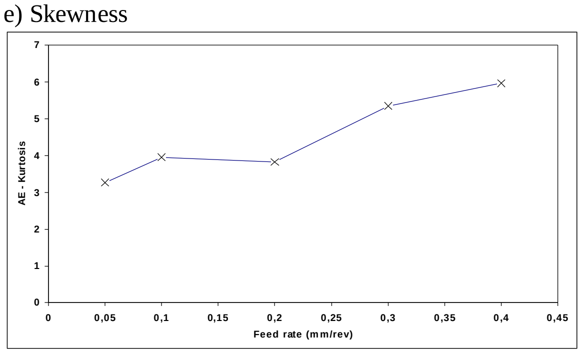
c) Standard deviation



d) Amplitude



e) Skewness



f) Kurtosis

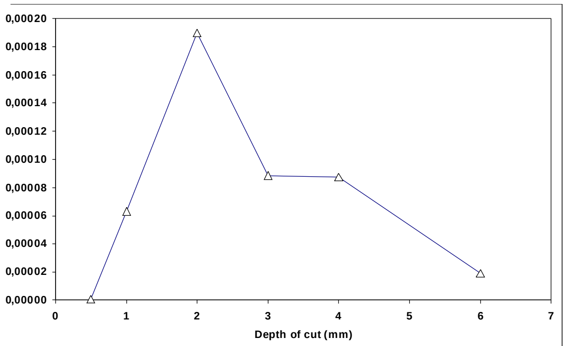
Fig. 3: Influence of the feed rate on the AE parameters (v_c = 120 m/min and doc = 0.5 mm).

Influence of the Depth of Cut on AE Signal

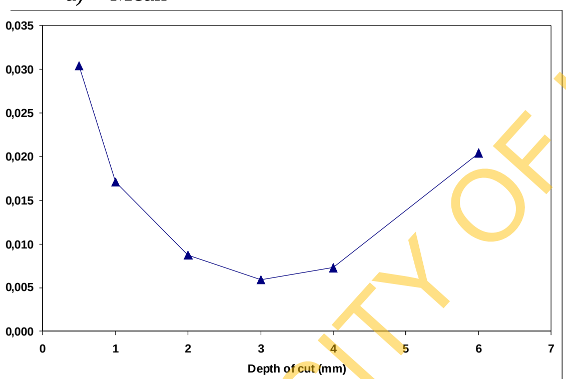
The variations in the AE parameters (mean, rms, standard deviation, amplitude, skewness and kurtosis) at different depth-of-cuts ranging from 0.5 – 6.0 mm with v_c = 120 m/min and f = 0.1 mm/rev are shown in

Figures 4(a-f). The mean value of AE signal increased with depth-of-cut up to 2 mm while the RMS values decreased. The reverse occurred with further increase in the depth-of-cut up to 6 mm. Figures 4(c & d) show increase in the standard deviation and amplitude of the AE signal at higher depth-of-cut.

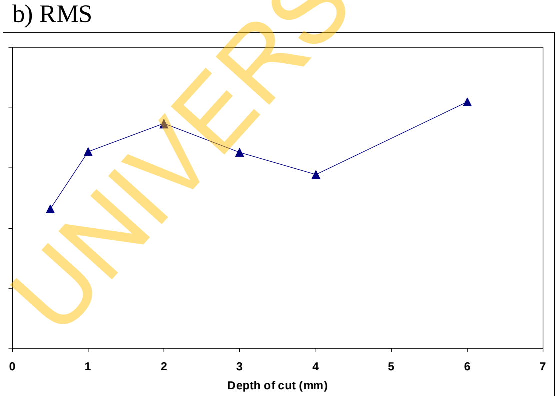
There was no distinctive trend between the observed skewness of the AE signal and the depth of cut (Figure 4(e)). However, the results showed high fluctuation between the negative and positive values. Similarly, as in other cases already described the kurtosis was over 3 (Figure 4(f)).



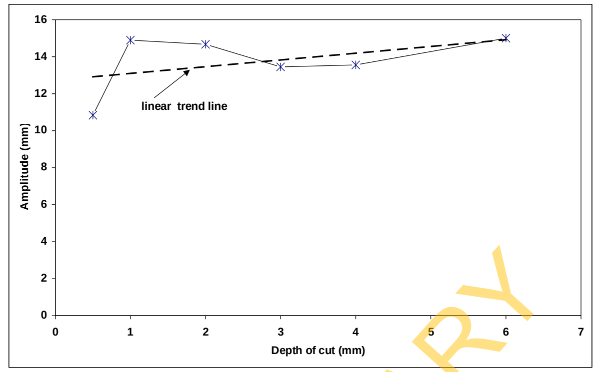
a) Mean



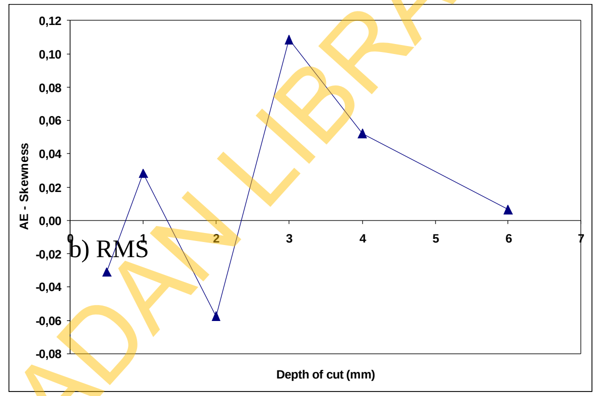
b) RMS



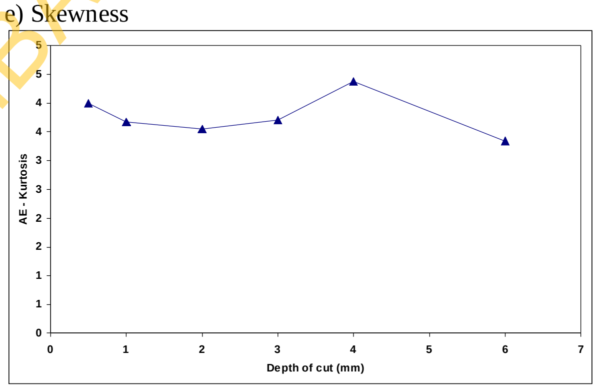
c) Standard deviation



d) Amplitude



e) Skewness



f) Kurtosis

Fig. 4: Influence of the depth-of-cut on the AE parameters (v_c = 120 m/min and f = 0.1 mm/rev)

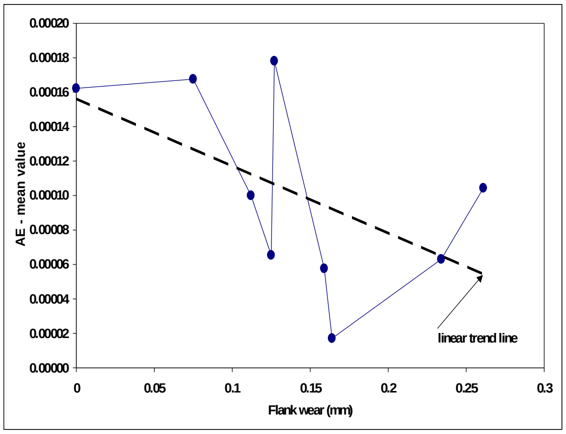
Influence of the Tool Wear on AE Signal

Figures 5(a-f) show the variations in AE signal for different tool flank wear levels. Increase in tool flank wear led to general reduction in the AE signal mean value (Figure 5(a)), standard deviation (Figure 5(c)), amplitude (Figure 5(d)) and skewness (Figure 5(e)), while RMS (Figure 5(b)) and kurtosis (Figure 5(f)) tended to increase with increase in tool flank wear.

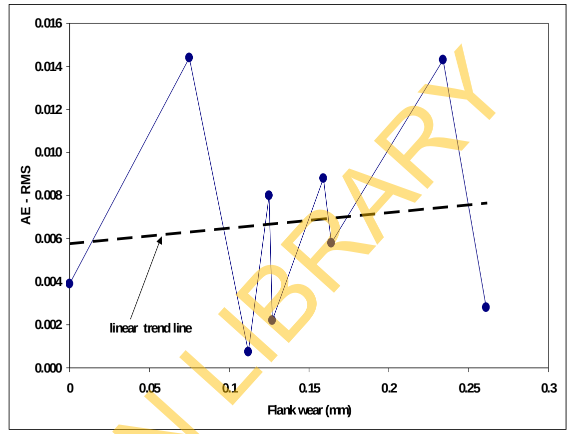
An increase in tool wear alters the cutting tool geometry and consequently diminishes the ability of the tool to shear the workpiece effectively. This promotes higher heat generation leading to elevated temperature in the primary and secondary shear zones and between the machined surface and tool rake face.

Furthermore, the strength of the workpiece material decreases. A combination of these factors contributes to increase damping rate, consequently attenuating and reducing the AE energy. Hence, changes in tool geometry can also change the acoustic emission signals and cutting forces.

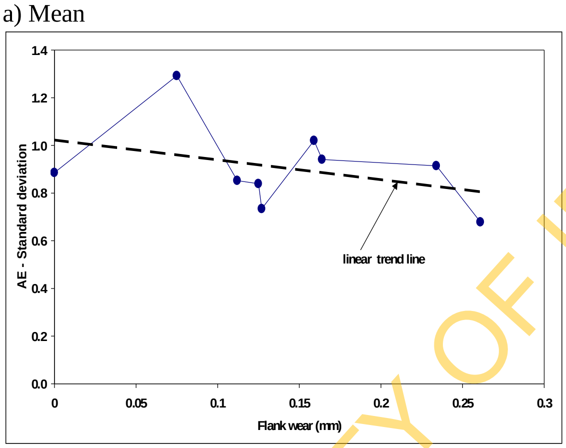
0.58 mm are shown in Figures 6(a-c). The AE spectra in both time and frequency domains were influenced by the wear state of the cutting edge. It can be observed that the AE level in the time domain (Figures 6(a-b)) decreased for worn out edge compared with fresh cutting edge.



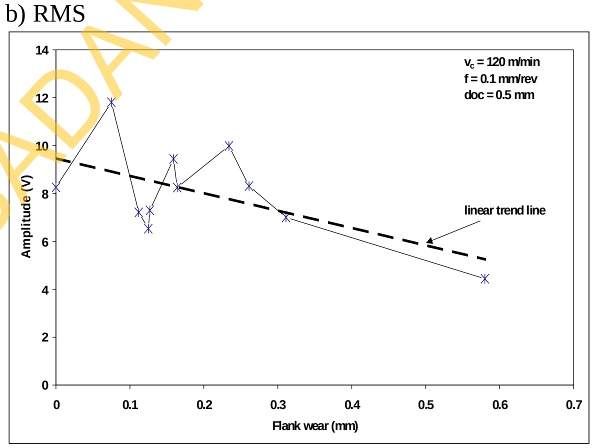
a) Mean



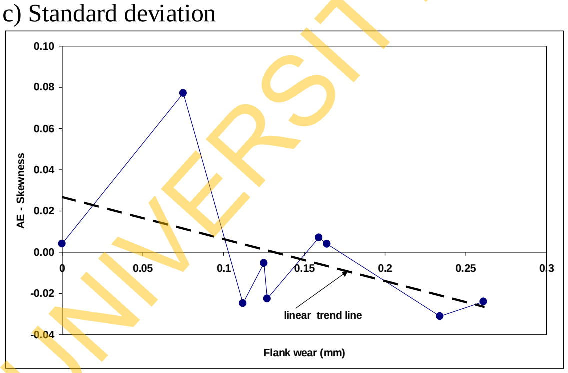
b) RMS



c) Standard deviation

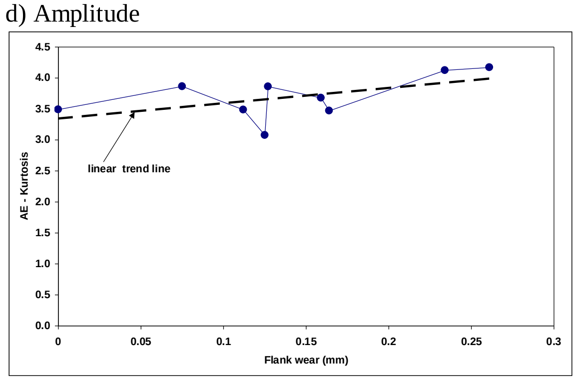


d) Amplitude



e) Skewness

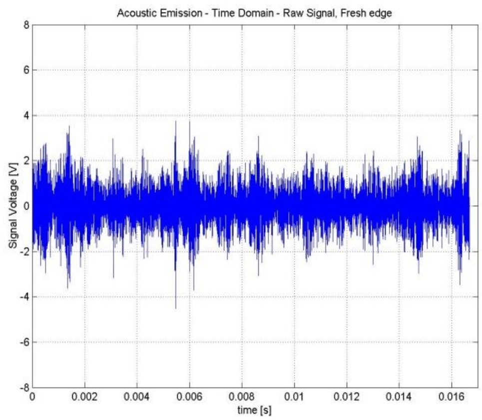
Fig. 5: Influence of the tool flank wear on the AE parameters (v_c = 120 m/min, doc = 0.5 mm and f = 0.1 mm/rev).



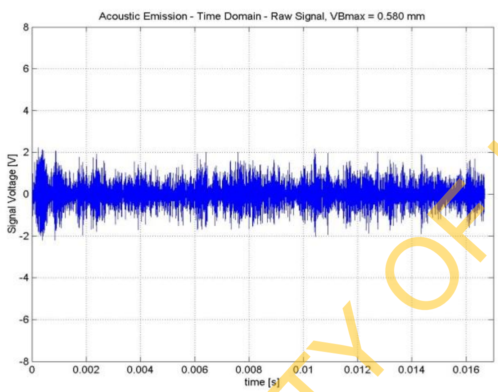
f) Kurtosis

Typical spectra obtained at cutting speed of 120 m/min, feed rate of 0.1 mm/rev and depth-of-cut of 0.5 mm for fresh cutting edge and a worn edge at the end of tool life with maximum flank wear (VB_{max}) of

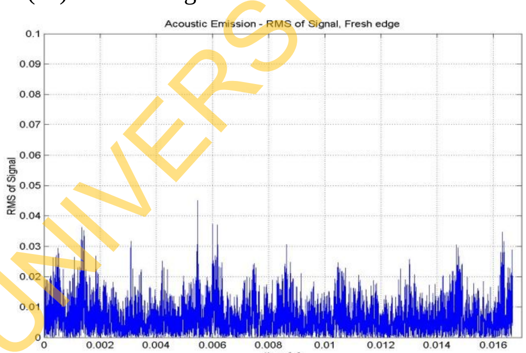
In the frequency domain, fresh tool edge had a high peak AE level, an attenuation phenomena occurred (increase in the damping rate) compared to the worn edge. Both fresh and worn cutting edges gave higher amplitudes for frequencies ranging from about 50 - 150 kHz, while the maximum amplitude occurred at 100 kHz. It can also be observed that the FFT spectra for both fresh and worn edges are similar in pattern. The only difference was that lower FFT values were recorded for worn cutting edge. This observation implied that the FFT values can be used as an efficient tool for tool wear condition monitoring when machining Ti-6Al-4V alloy.



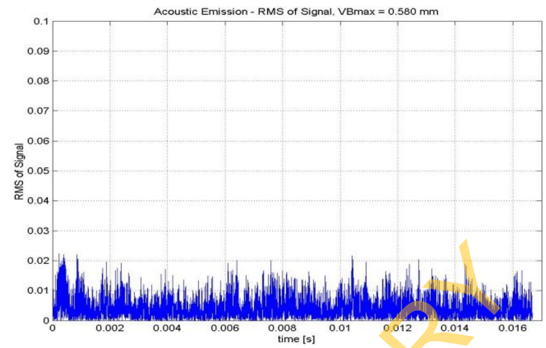
(1a) Raw AE signal



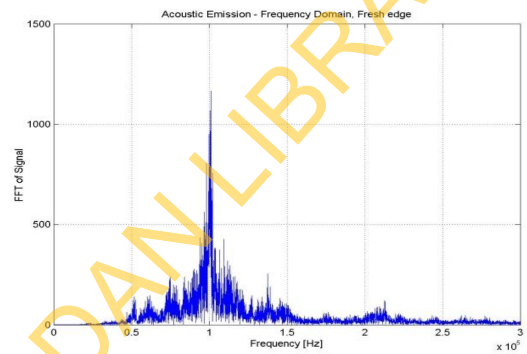
(1b) Raw AE signal



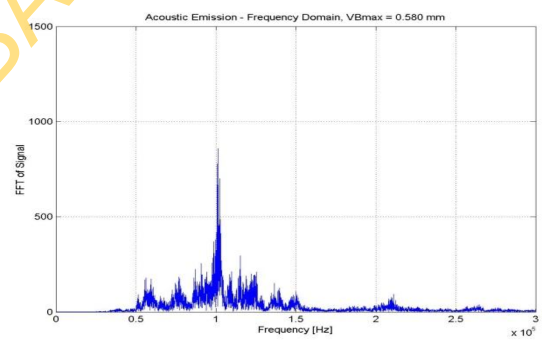
(2a) RMS signal



(2b) RMS signal



(3a) Frequency



(3b) Frequency

Fig. 6: AE signal in time and frequency domains for fresh and worn cutting edges

CONCLUSIONS

The influence of cutting parameters and tool wear on the acoustic emission signal in high-speed turning of Ti-6Al-4V alloy with uncoated cemented carbide inserts has been investigated. Based the observations, the following conclusions can be made:

1. Higher cutting speed led to increase the AE mean, RMS, standard deviation and amplitude of the raw signal and reduced skewness and kurtosis.
2. Increase in the feed rate reduced the AE mean and RMS, while the standard deviation and amplitude increased slightly. The skewness showed negative values at lower and higher feed rates and positive values at intermediate speed conditions while the kurtosis always increased with higher feed rates.

3. Increase in depth-of-cut slightly increased the AE mean, standard deviation and amplitude of the raw signal while the RMS value reduced at higher depth of cut. There was a random relation between depth of cut and skewness while the kurtosis reduced slightly at higher depth-of-cuts.
4. An increase in tool wear reduced the AE mean, standard deviation and amplitude. The RMS values fluctuated highly but remained stable. Skewness at lower flank wear was positive and became negative at intermediate and higher flank wear values while the kurtosis increased with increase in tool wear.
5. Frequency domain analyses showed that the frequency spectrum does not change with increase in tool wear and that the amplitude at each frequency decreased with increasing tool wear. This could be a good indicator for tool wear monitoring.

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