EVALUATION OF THE APPLICABILITY OF ACOUSTIC EMISSION MONITORING IN TURNING OF Ti-6Al-4V WITH HIGH-PRESSURE COOLANT SUPPLY

Wisley Falco Sales, e-mail: wisley@pucminas.br

Pontifical Catholic University of Minas Gerais - PUC Minas, Mechanical and Mechatronics Engineering, Manufacturing Research Centre, B. Horizonte, MG, Brazil.

John Bonney, e-mail: bonnyj@lsbu.ac.uk

Emmanuel O. Ezugwu: ezugwuo@lsbu.ac.uk

Machining Research Centre, London South Bank University, London, SE 1 0AA, UK.

Abstract. The main objective of this study is to investigate the applicability of monitoring technique based on acoustic emission in high speed turning of Ti-6Al-4V alloy with cemented carbide inserts at high-pressure coolant supply. Piezoelectric sensor and data acquisition system were used for measuring and storing the signals. The time and frequency domain analyses were conducted using the raw signals acquired. Results obtained show no immediate potential of this technique for process condition monitoring when turning the titanium alloy using high-pressure coolant supply. This is caused by high noise generated on impact of the high-pressure coolant against the work material. This high noise has similar range of amplitude and frequency as that generated when turning the titanium alloy.

Keywords: High Speed Turning; Ti-6Al-4V; Signal Monitoring; Acoustic Emission; Tool wear.

1. INTRODUCTION

Titanium and its alloys are used mostly in the aerospace industry due to their combination of superior properties including high specific strength that are maintained at very high temperature conditions. Complex titanium alloy parts are produced by conventional machining processes such as, turning, milling, drilling, boring, etc. Most study on the machining of titanium-based alloys describes chip formation and its control, tool materials, failure modes and wear mechanisms (Komanduri and Von Turkovich, 1981, Ezugwu and Wang, 1997, Barry et al, 2001, Ezugwu et al, 2003) Despite the high usage of titanium alloys, they are very expensive to machine relative to conventional alloys such as steels. This is because machining of titanium alloys are hampered by the severe tribological conditions that occur at the cutting interfaces resulting to increased chip-tool interface temperature, tool wear, dimensional tolerances, surface roughness, power consumption, cutting forces, vibration, acoustic emission, etc. Challenges to reduce machining costs are in evidence and tool materials, coatings, coolants and its application method are constantly being developed as well as investigation of their usage in the machining of titanium alloys (Ezugwu and Wang, 1997). Cutting fluids applied at pressures between 7 and 30 MPa (flow rate between 10 to 30 l/min) have been successfully used for the machining of titanium and nickel alloys (Ezugwu et al, 2005a and b, Ezugwu and Bonney, 2004).

Acoustic emission (AE) has been used since the 1980's for controlling machining processes (Kannatey-Asibu and Dornfeld, 1982, Diniz et al, 1992, Tönshoff et al, 2000, Li, 2002, Chungchoo and Saini, 2002, Haber et al, 2004, Sales et al, 2007). It is defined as the phenomenon whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material. Kannatey-Asibu Jr. and Dornfeld (1982) also defined AE as the transient elastic energy spontaneously released in materials undergoing, deformation, fracture or both. It is dependent on basic deformation mechanisms such as dislocation motion, grain boundary sliding, twinning and vacancy coalescence. The AE released under these circumstances can be related to the grain size, dislocation density and the distribution of second-phase particles in crystalline materials during the deformation process. The energy contained in an AE and the rate at which it is dissipated is strongly dependent on the rate of deformation (strain rate), the applied stress and the volume of the participating material. The possible sources of AE during metal cutting processes are: 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 and Dornfeld, 1982, Li, 2002, Lemaster et al, 1985). Mechanical properties of the workpiece and tool material, such as, hardness, toughness, and work hardening rate are relevant for AE energy generation. Surface integrity, mainly sub-surface hardened layer, or the white layer generated after hard turning or grinding of steels can change the intensity of the AE energy (Tönshoff et al, 2000). On the other hand the tribological aspects existing at the rake-chip and flank-workpiece interfaces must be considered for a better understanding of the AE energy level.

AE in most cases bear a good relationship to tool wear and surface roughness and is therefore an efficient means for monitoring machining processes (Diniz et al, 1992). The main aim of this study is to apply acoustic emission monitoring technique when turning Ti-6Al-4V alloy at conventional and high-pressure coolant supplies in order to achieve better understanding of the relationship between AE levels and tool wear.

2. EXPERIMENTAL PROCEDURES

The work material is Ti-6Al-4V bar with a length of 300 mm and a diameter of 200 mm. The machining trials were carried out on a CNC lathe with an 11 kW drive and rotational spindle speed ranging from 18 to 1,800 rpm. The tool material is a cemented carbide, ISO K10 grade, specification SNMG 190616-M1. A high lubricity emulsion diluted with water to 6% concentration was used as coolant. The high-pressure coolant delivery system has a power of 30 HP, a maximum flow rate of 93.6 l/min and maximum pressure of 21 MPa. Figure 1 shows a schematic illustration of the cutting fluid application directions.

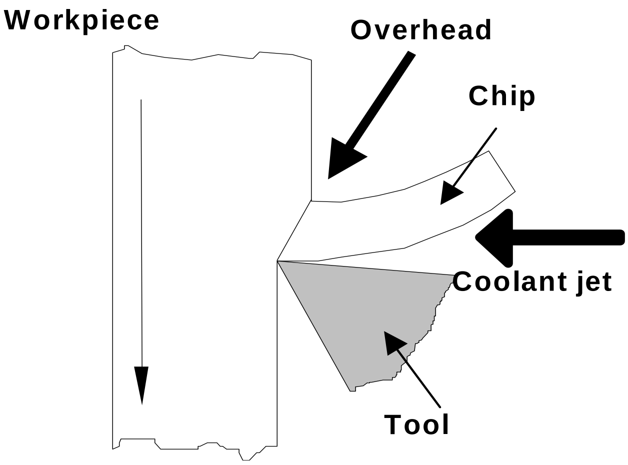


Figure 1 - A schematic illustration of the directions of application of the cutting fluid.

Tool rejection criteria stipulated are:
Maximum flank wear: VB_{max} = 0.8 mm;
Nose wear: V_C = 0.8 mm.
Fracture or catastrophic failure of the cutting tool.

The acoustic emission signals generated during the machining trials were captured with a system composed of a coupler and sensor (manufactured by Kistler). The AE sensor was fixed to the tool holder by a bolt fixture.

Turning tests were carried out at the following cutting conditions:
Cutting speed (v_c); 150 m/min;
Feed rate (f): 0.1 mm/rev;
Depth of cut (doc): 0.5 mm.

Cooling environments: conventional coolant flow and coolant pressures of 7 MPa (70 bar, flow rate of 25.4 l/min and exit velocity of 65.06 m/s per hole) and 11 MPa (110 bar, flow rate of 30 l/min and exit velocity of 79.02 m/s per hole).

All the machining trials were conducted with a fresh cutting edge and each test was repeated. Figure 2 shows the high-pressure system used in the machining trials while the experimental set-up employed for the machining trials is illustrated schematically in Fig. 3.

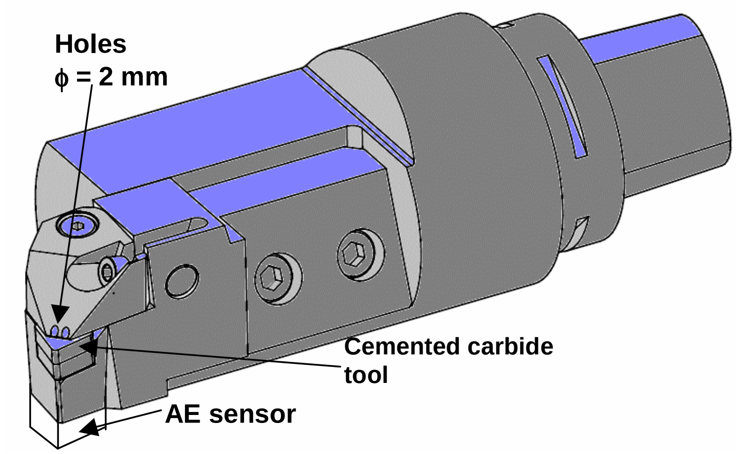


Figure 2 – High-pressure system used in the trials.

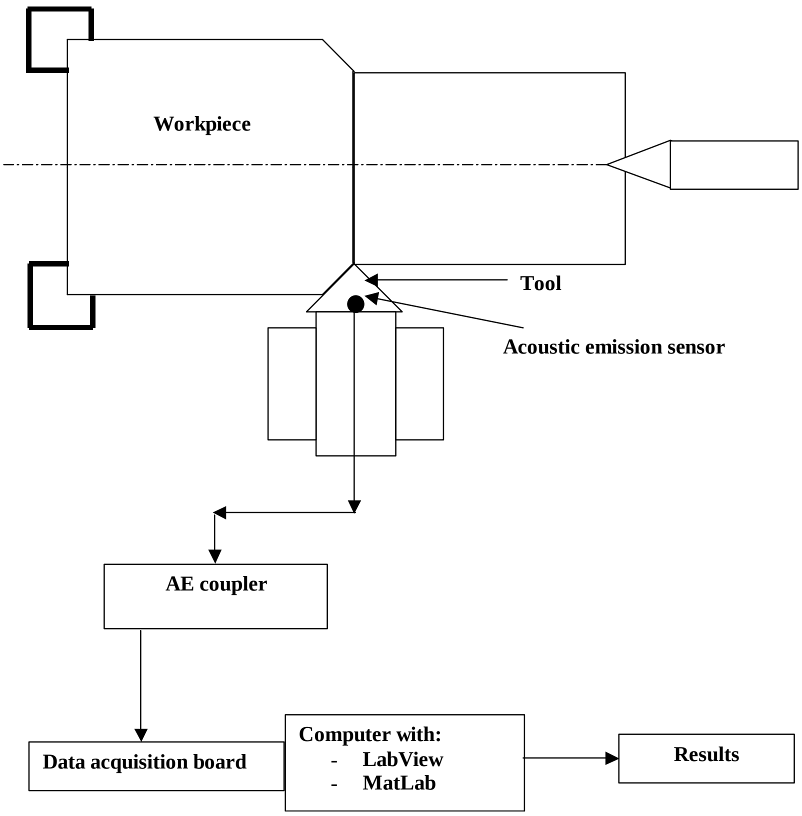


Figure 3 - Experimental set-up.

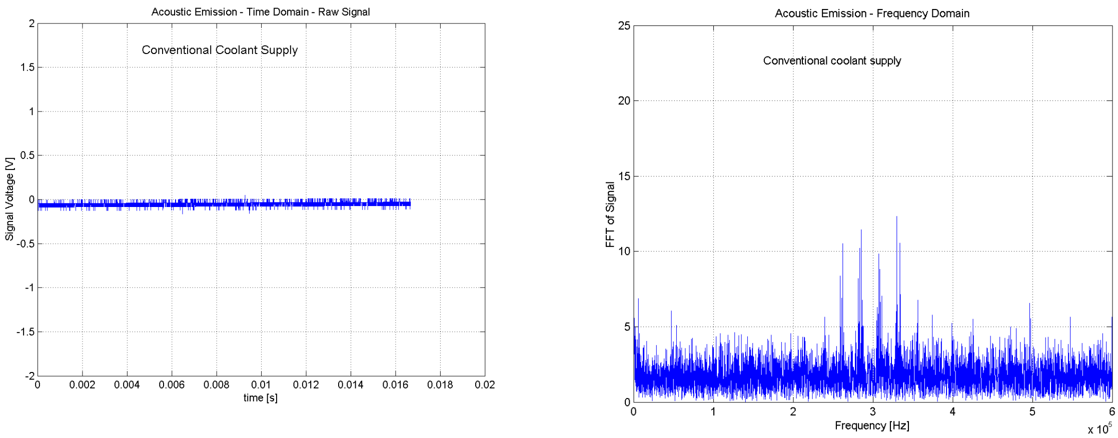
A data acquisition system, 100 MHz with 2 acquisition channels and one trigger was used for the tests. Lower frequencies of mechanical displacements and noises were filtered using high pass filter with cut off frequency of 50 KHz during machining. No filtered AE signals were recorded with high-pressure coolant supply prior to starting the turning trials. The lathe spindle is in the "on" position. All AE signals were captured at a sample rate of 600 KHz with 10,000 data points. Each machining trial was conducted for 10 seconds during which 7 files were acquired each recording 10,000 data points. Statistical analysis of the data was carried out using Matlab program.

3. RESULTS AND DISCUSSIONS

The study is divided into three parts. The first part involves acquiring the AE raw signal with the spindle and cutting fluid at conventional and high-pressure (7 and 11 MPa) coolant supply at on position, without cutting. The second stage involved recording the AE raw signal when machining with a fresh tool edge at the same conditions as in the first stage. The last stage involved recording the AE raw signal at the end of tool life when significant tool wear has occurred. The results from these parts were compared and analysed and possible correlations between them were evaluated.

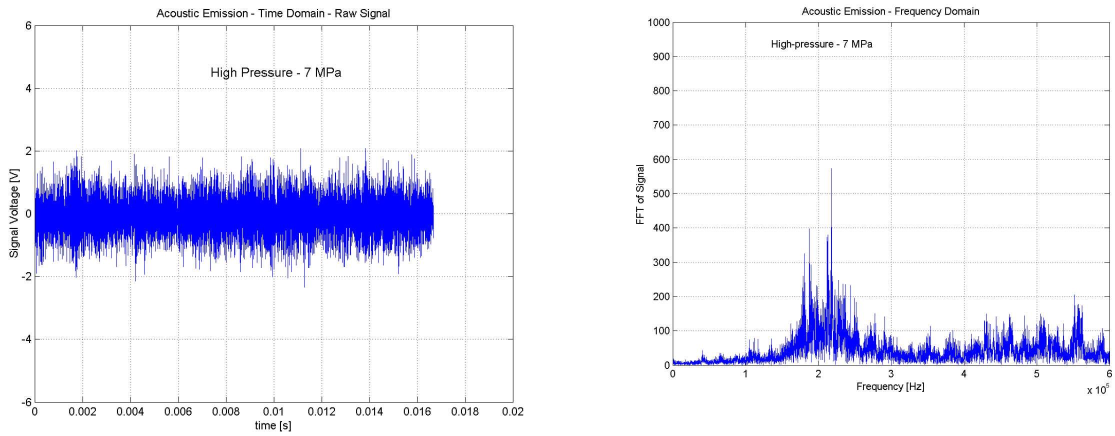
3.1. AE signal recorded with no cut - spindle rotation and coolant supply at ON position

Figures 4 to 6 show recorded results using conventional and high-pressure coolant supplies of 7 and 11 MPa, respectively when no cut was taken.



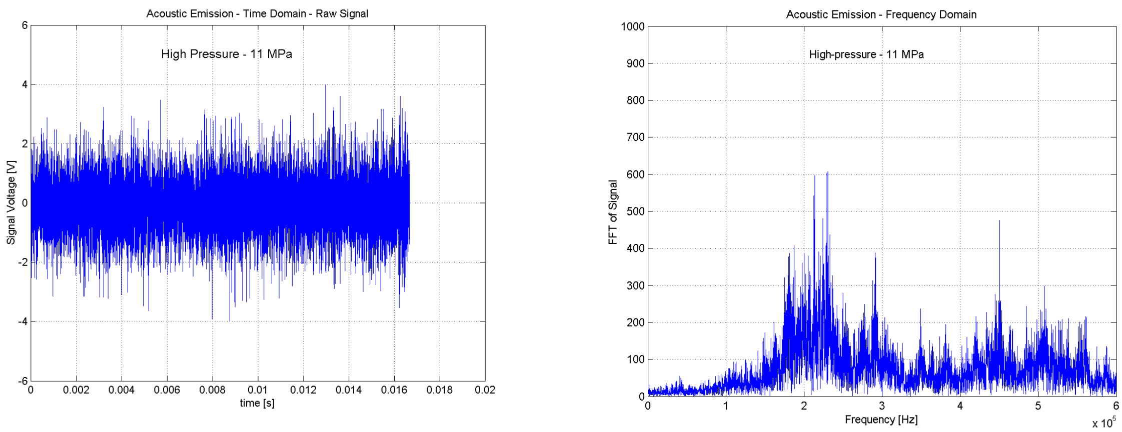
a) AE raw signal. b) AE FFT signal.

Figure 4 - AE raw signal measured with no cut – conventional coolant supply.



a) AE raw signal. b) AE FFT signal.

Figure 5 - AE raw signal measured with no cut – high-pressure of 7 MPa.



a) AE raw signal. b) AE FFT signal.

Figure 6 - AE signal recorded with no cut – high-pressure of 11 MPa.

Conventional coolant supply shows predominance of the white level (Fig. 4b), except for some energy peaks at frequencies between 260 and 320 kHz. When these values were measured at high-pressure of 7 MPa high peaks were observed between 160 and 240 kHz (Fig. 5b). At higher pressure of 11 MPa (Fig. 6c) the spectrum is similar to that of 7 MPa, but with evidence of other higher peaks at 280 and 430 KHz.

Table 1 shows mathematical parameters (mean, amplitude, standard deviation, Skewness and Kurtosis) calculated from AE raw signal, with no cut, but with the spindle and coolant in the on position.

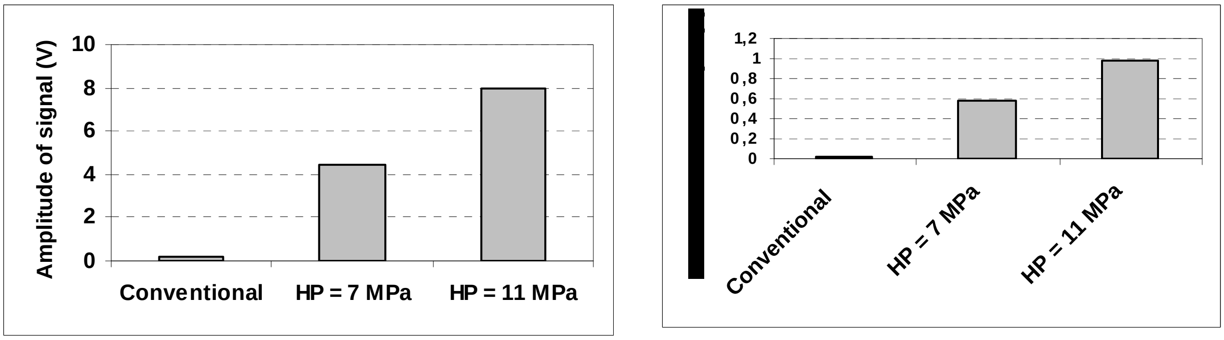
Table 1 – Parameters calculated from AE raw signal – with no cut.

	Statistical parameter					
Condition evaluated	Mean (V)	Amplitude (V)	Standard deviation (V)	RMS (V)	Skewness	Kurtosis
Conventional coolant supply	-0.4440	0.2090	0.0209	2.6125E-4	-0.8578	4.8109
High-pressure – 7 MPa	-0.0607	4.4191	0.5896	7.9121E-4	0.0204	3.1055
High-pressure – 11 MPa	-0.0595	7.9706	0.9802	0.0148	0.0340	3.1450

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. The fact that Sk > 0, for both high-pressure conditions, implies that there is higher concentration of AE signal below the mean value (μ). On the contrary, for Sk < 0 as observed with conventional coolant supply shows that there is concentration of AE signal above the mean value.

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 Kurtosis implies flat characteristics. Kurtosis of the raw signal was greater than 3 (Ku > 3) in all conditions investigated. Ku is equal to 3 for normal distribution. The fact that Ku > 3 implies that a high-peaked AE distribution is generated which is dominated by high amplitude signals and is highlighted for conventional coolant supply condition.

Figure 7 shows plots of the amplitude and the standard deviation of the AE raw signal. There is evidence that at high-pressure the AE level is higher than at conventional coolant supply. Both amplitude and standard deviation increased significantly by applying the cutting fluid at high-pressure.



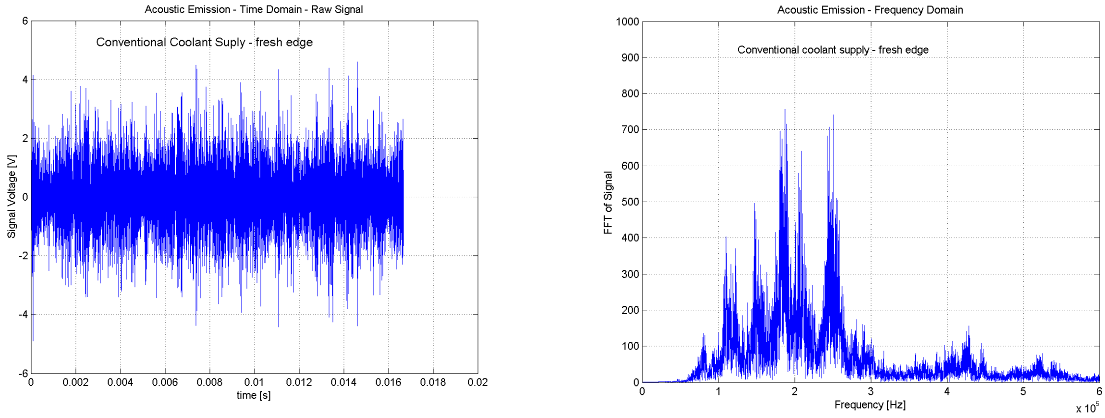
a) Amplitude of the AE raw signal. b) Standard deviation of the AE raw signal.

Figure 7 - Signal recorded with no cut.

This high AE signal level is only due to impact of the cutting fluid (at higher velocity, flow rate and pressure) on the workpiece and the tool holder as there is no cut in the test. On the monitoring point of view, this is considered as an extremely negative behaviour because this is an unwanted signal, or a noise.

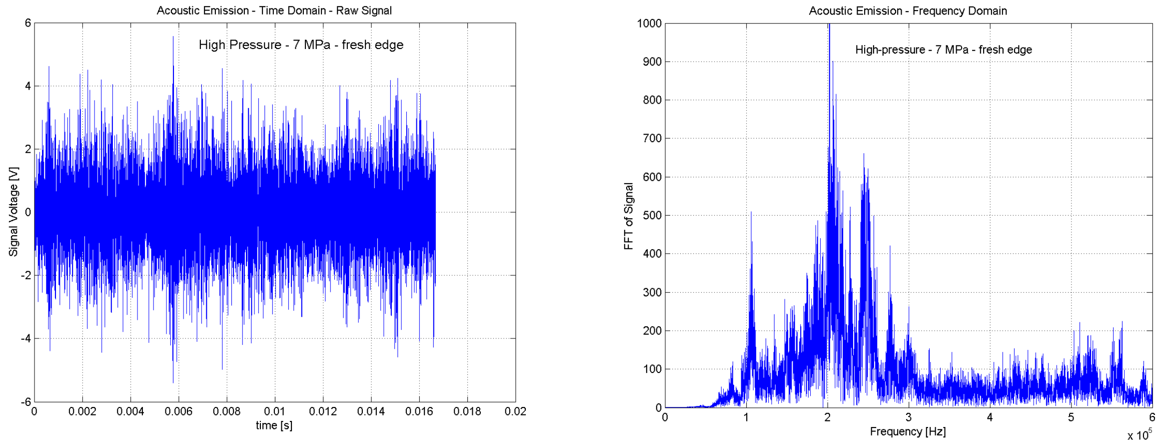
3.2. AE signal recorded when machining with fresh tool edge

Figures 8 to 10 show the recorded results when machining with fresh tool edge using conventional and high-pressure coolant supplies of 7 and 11 MPa, respectively.



a) AE raw signal. b) AE FFT signal.

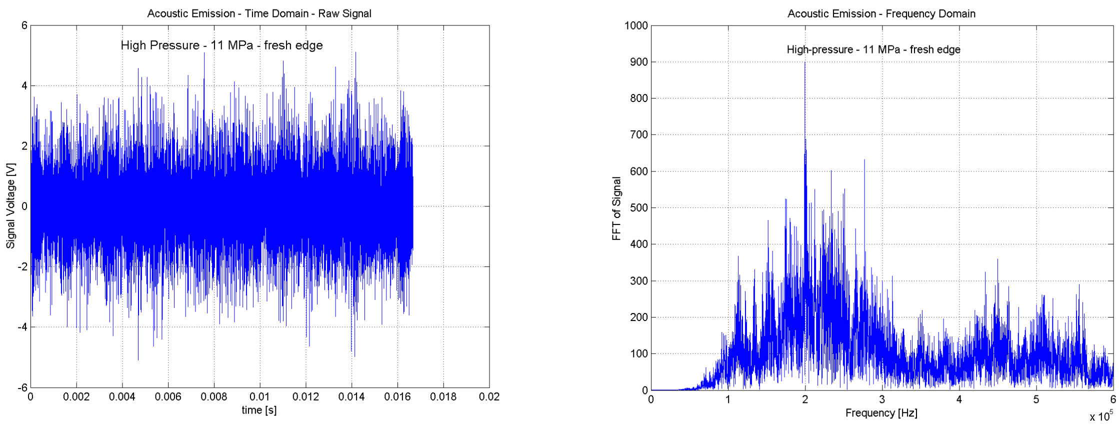
Figure 8 - Signal recorded when machining with fresh tool under conventional coolant supply.



a) AE raw signal. b) AE FFT signal.

Figure 9 - AE signal recorded when machining with fresh tool under high-pressure of 7 MPa.

Figure 8(b) illustrates the presence of harmonics at frequencies between 100 and 260 kHz under conventional coolant supply. At high-pressure of 7 MPa, high peaks can be observed between 100 and 300 kHz (Fig. 9b). The spectrum at higher-pressure of 11 MPa (Fig. 10b) shows many harmonics between 120 and 500 KHz.



a) AE raw signal. b) AE FFT signal.

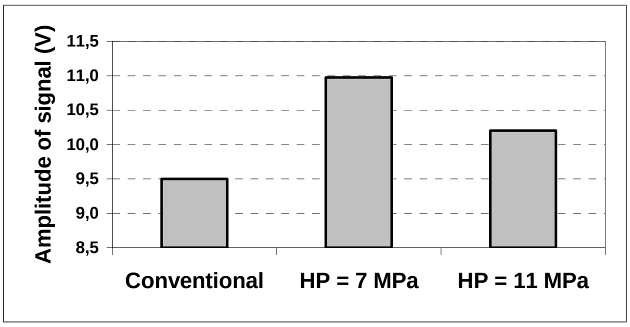
Figure 10 - AE signal recorded when machining with fresh tool under high-pressure of 11 MPa.

Table 2 shows mathematical parameters (mean, amplitude, standard deviation, Skewness and Kurtosis) calculated from AE raw signal when machining with fresh tool edges.

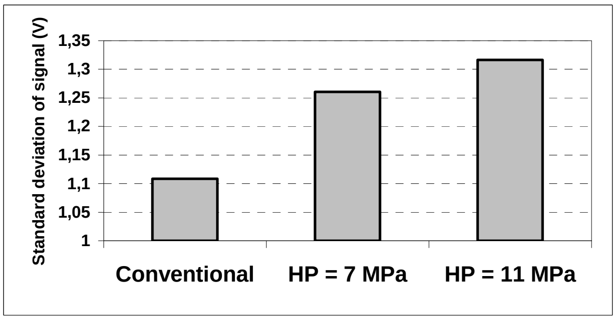
Table 2 – Parameters calculated from AE raw signal – machining with fresh tool edges.

	Statistical parameter					
Condition evaluated	Mean (V)	Amplitude (V)	Standard deviation (V)	RMS (V)	Skewness	Kurtosis
Conventional coolant supply	-1.3219E-4	9.4995	1.1082	0.0044	0.0323	3.3792
High-pressure – 7 MPa	-1.3253E-4	10.9739	1.2608	0.0069	-0.0125	3.3041
High-pressure – 11 MPa	-3.0407E-5	10.2035	1.3165	0.0046	0.0374	3.1291

This table show Skewness greater than zero (Sk > 0), for conventional and higher-pressure of 11 MPa and Sk < 0 for high-pressure of 7 MPa. Kurtosis of the raw signal was greater than 3 (Ku > 3) for all conditions investigated and show the tendency to reduce with increasing the coolant pressure.
Figure 11 are plots of amplitude and standard deviation of the AE raw signal. The AE level is higher with high-pressure coolant supplies than with conventional coolant supply. Similar trace was obtained when no cut was taken. Both amplitude and standard deviation increased when machining at higher-pressures.



a) Amplitude of the AE raw signal.



b) Standard deviation of the AE raw signal.

Figure 11 - Signal recorded when machining with fresh tool.

4. CONCLUSIONS

From this study the following conclusions can be drawn:

1. AE signal at high-pressure coolant supply generated significant noise with similar magnitude and frequency levels as AE signal generated during machining. This high level of noise can compromise its utilization as a condition monitoring technique.
2. An increase in the coolant pressure, from conventional to high-pressure, tends to increase the AE signal level under all the cutting conditions investigated.
3. Coolant applied at high-pressure tends to disperse the harmonics, between 120 kHz to 500 kHz, when evaluated on frequency domain. This therefore requires extensive filtering of the noise level in order to obtain reliable results using the AE technique.

AKNOWLEDGMENTS

The authors would like to acknowledge support from Rolls-Royce plc which enable this study to be carried out. One of the authors acknowledges the support of the Brazilian agency for research fund (CAPES – Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), project number PDE 0333-04-2.

5. REFERENCES

Barry, J., Byrne, G. and Lennon, D. (2001), Observations on chip formation and acoustic emission in machining Ti-6Al-4V alloy, International Journal of Machine Tools & Manufacture, 41, pp. 1055-1070.
Chungchoo, C. and SAINI, D. (2002), A computer algorithm for flank and crater wear estimation in CNC turning operations, International Journal of Machine Tools & Manufacture, 42, pp. 1465-1477.

Diniz, A.E., Liu, J.J. and Dornfeld, D. (1992), Correlating tool life, tool wear and surface roughness by acoustic emission in finish turning, Wear, 152, pp. 395-407.

Ezugwu, E.O. and Wang, Z.M. (1997), Titanium alloys and their machinability – a review, Journal of Materials Processing Technology, 68, pp. 262-274.

Ezugwu, E.O., Bonney, J. and Yamane, Y. (2003), An overview of the machinability of aeroengine alloys, Journal of Materials Processing Technology, 134, pp. 233-253.

Ezugwu, E.O., Silva, R.B., Bonney, J. and Machado, Á.R. (2005a), Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies, International Journal of Machine Tools and Manufacture, Volume 45, Issue 9, pp. 1009-1014.

Ezugwu, E.O., Bonney, J., Fadare, D.A. and Sales, W.F. (2005b), Machining of nickel-base, Inconel 718, alloy with ceramic tools under finishing conditions with various coolant supply pressures, Journal of Materials Processing Technology, In Press, Corrected Proof, Available online 9 March 2005.

Ezugwu, E.O. and Bonney, J. (2004), Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools, Journal of Materials Processing Technology, Volumes 153-154, 10 November 2004, pp. 1045-1050.

Haber, R.E., Jiménez, J.E., Peres, C.R. and Alique, J.R. (2004), An investigation of tool-wear monitoring in a high-speed machining process, Sensors and Actuators, IN PRESS.

Kannatey-Asibu Jr, E. and Dornfeld, D.A. (1982), A study of tool wear using statistical analysis of metal-cutting acoustic emission, Wear, 76, pp. 247-261.

Komanduri, R. and Von Turkovich, B.F. (1981), New observations on the mechanism of chip formation when machining titanium alloys, Wear, 69, pp. 179-188.

Lemaster, R.L., Tee, L.B. and Dornfeld, D. (1985), Monitoring tool wear during wood machining with acoustic emission, Wear, 101, pp. 273-282.

Li, X. (2002), A brief review: acoustic emission method for tool wear monitoring during turning, International Journal of Machine Tools & Manufacture, 42, pp. 157-165.

Sales, W.F., Bonney, J., Ezugwu, E.O. and Fadare, D. (2007), Influence of cutting parameters on acoustic emission signal when high speed turning of the Ti-6Al-4V alloy, To be published.

Tönshoff, H.K., Jung, M., Mänuel, S. and Rietz, W. (2000), Using acoustic emission signals for monitoring of production processes, Ultrasonics, 37, pp. 681-686.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.