CHAPTER 2
ACOUSTIC EMISSION BASED TOOL WEAR MONITORING

This chapter discusses Acoustic Emission (AE) based tool wear monitoring in face milling operations. General introduction to AE and AE in metal cutting are presented in section 2.1 to 2.3. Experimental setup for AE data acquisition and its analysis for tool wear monitoring is presented in section 2.5 to 2.7.

2.1 Introduction:

Acoustic emission (AE) and microseismic are naturally occurring phenomena which man has observed from early times. The cracking of rocks and the breaking of bones were among the earliest. Potters observed the sounds of cracking of clay vessels cooling quickly in the kiln. These were audible acoustic emissions by which the potter knew that his creations were defective and structurally failing. In metals, it would be reasonable to assume that the first true AE heard was the ‘cry’ of tin, the audible emission produced by mechanical twinning of pure tin during plastic deformation.

Incidental observations of audible sounds emitted by metals during the course of studying various metallurgical phenomena, primarily twinning and martensitic phase transformations, are reported in the literature as early as 1916. Small sharp noises were reportedly audible at the distance of several meters during discontinuous yielding and Luders band formation in alloys of Al, Cu and Mn. Joseph Kaiser from Germany reported the first comprehensive investigation into the phenomenon of acoustic emission.

AE refers to the stress waves generated by dynamic processes in materials. Emission occurs as a release of a series of short impulsive energy packets. The energy thus released travels as a spherical wave front and can be picked up from the surface of a material using highly sensitive transducers usually electromechanical placed on the surface of the material. The wave thus picked up is converted into electrical signal, which
on suitable processing and analysis can reveal valuable information about the source causing the energy release. Fig. 2.1 shows the AE generation process [20,63].

![Fig. 2.1 Generation of AE](image)

2.2 Acoustic emission signals –

AE signals are transient in nature. The transducer output can be modeled crudely as a decaying sinusoid. This model is applicable only for signals that can be identified as individual bursts with discernible time gap between two successive events. If the burst rate is very high, events may occur very close to one another and sometimes even overlapping, in which case it is termed as 'continuous emission'.

![Continuous Emissions vs. Burst Emissions](image)

**Fig. 2.2 Two Types of AE**
Fig. 2.2 shows Two Distinct Types of AE.

(i) The high amplitude, somewhat erratic, low frequency type called the 'burst emission', which is generally associated with surface events such as slip line formation and surface microcracks.

(ii) The lower amplitude, steady, high frequency type called the 'continuous emission' that is generally associated with internal mechanism activity being normally observed during tests of tensile specimens [30].

2.2.1 Sources of AE

Sources of acoustic emission include many different mechanisms of deformation and fracture. Earthquakes and rock bursts are the largest naturally occurring emission sources. Sources that have been identified in metals include moving dislocations, slip, twinning, grain boundary sliding, crack initiation, crack growth etc. Other mechanisms like leaks, cavitation, friction, growth of magnetic activation domains, movement of magnetic domain wells, phase transformations are also detectable by AE equipment. These sources are termed as secondary or pseudo sources [58].

2.2.2 AE Signal Parameters -

Fig. 2.3 shows a typical emission signal and some of the terminology involved with signal analysis.
a) **Event** – An event is a single occurrence of an AE signal activity. An event begins when the first signal pulse crosses the threshold and ends when the last pulse crosses the threshold.

b) **Ring down count (RDC)** – The number of times the signal amplitude crosses the preset reference threshold. And the number of times the signal has crossed the threshold since the beginning of the test is the Cumulative count.

c) **Rise time** – This is the time duration for the rise from an event’s first threshold crossing until the signal reaches its peak amplitude. This is measured in microseconds.

d) **Event duration** – It is defined as that amount of time that passes between the event’s first threshold crossing and its last crossing. It is measured in microseconds.

e) **Peak amplitude** – It is the highest amplitude reached by the AE signal during an event. It is measured in decibels (dB). This is a very important parameter because it directly determines the detect ability of the AE event.

f) **MARSE** – Sometimes known as energy counts, is the measured area under the rectified signal envelope, MARSE is preferred over counts because it is sensitive to amplitude as well as duration, and it is less dependent on threshold setting and operating frequency.

g) **Mean rise time per event** – It can be obtained by summing the rise time value in each time interval and dividing the same by the number of events in that interval.

h) **Reference threshold** – A preset voltage level that has to be exceeded before an AE signal is detected and processed. The threshold may be fixed or automatic [68, 74, 78].

### 2.3 Acoustic emission in Metal cutting

Acoustic emission has been extensively researched and found to be one of the most promising techniques for tool condition monitoring. Its attractiveness results from its generation by processes in the cutting zone, which are dependent on the cutting parameters of the process being monitored. Initial studies in this respect have emphasized empirical relations between emission signal and flank wear and relations between AE and
the cutting parameters have been formulated, where good correlation has been found between the emission signal, strain rate and cutting speed [47]. The analysis of acoustic emission signals generated during machining has been proposed as a technique for studying both the fundamentals of the cutting process and tool wear, and as a methodology for detecting tool wear and failure on-line [33].

![Diagram of chip formation](image)

Fig. 2.4 & 2.5 Possible Sources of AE Signals In Metal Cutting

Moriwaki (1983) [30] with reference to fig. 2.4 & 2.5 suggests that the following are possible sources of AE in the metal cutting process:

(a) The extensive plastic straining that occurs in the primary shear zone during chip formation (1),
(b) Rubbing between the chip underside and the tool face, secondary shear zone (2),
(c) Rubbing between the tool flank and the newly machined workpiece surface, tertiary shear zone (3)
(d) Rubbing between chips and chip breaker (4),
(e) Cracking of work material (5),
(f) Collision and breakage of chip (6 & 7).

Kannatey-Asibu (1982) further identified
(g) Tool fracture
(h) Possibly cutting fluids applied in jet form under considerable pressure.

Sources (a)-(d) are representative of the continuous emissions, whilst (e)-(g) are representative of burst emissions.
Flank wear occurs primarily as a result of the rubbing action between the flank face of the tool and the newly formed workpiece surface, whilst crater wear is concerned with the contact between the chip and the rake face of the tool. The progress of wear in either zone, especially crater wear, is strongly dependent upon the temperature state in that area, which is in turn dependent upon the extent, or rate of deformation in that zone. Therefore AE signals from the primary, secondary and tertiary zones collectively are either directly or indirectly influenced by the extent of tool wear [30].

![Diagram](image.png)

Fig. 2.6 Major Sources of AE in Face Milling

It is clear that, whilst AE based monitoring methods may be successfully applied in the monitoring of continuous machining processes like turning, the discontinuous nature and process variability associated with milling cause limitation in its application. Some observations made with respect to face milling process by Diei and Dornfeld (1987) [11] and which deserve special mention are as follows (Fig. 2.6).

1. The discontinuous nature of the cutting introduces two additional sources of AE at the tool entry into and exit from the workpiece. The signal level from both sources is quite high and results in entry and exit peaks in the RMS AE signal.
2. The chip thickness varies throughout each cutting cycle; this generates varying tool forces and contact conditions at the tool rake surface.
3. At the tool exit, chips sometimes adhere onto the tool and are carried into the next cut, causing chip congestion. This introduces random variations in the level and characteristics of the signal generated.
(4) In the multi-tooth cutting configuration, more than one cutting edge may be active at
the same time and this implies several AE and cutting force generators.

2.4 AE Technique for Tool Wear Monitoring –

The use of AE for tool wear monitoring has attracted more and more attention
because of its non-intrusiveness, ease in operating and fast dynamic response. The
acoustic emission sensor is small and easy to be positioned on workpiece or tools,
therefore the size and weight of the workpiece or tools do not have a strong bearing on
the performance of the sensor. The dependency of the AE signal on the cutting
parameters becomes the key factor governing the applicability of AE sensing to
machining process monitoring. The other significant advantages are as follows –

1) Changes in AE signal level occur almost simultaneously whereas the change in the
force level occurs only after the tool has broken or chipped-off. Thus AE can be
effectively used to detect tool fracture or chipping for taking suitable timely action.

2) The frequency range of the AE signals is well above that of mechanical vibrations
and noises, and hence no chance of contamination by these.

3) According to Iwata & Moriwaki (1977), AE signals for different cutting materials are
basically similar in spite of the differences in their mechanical properties and cutting
conditions.

4) The AE transducer can be easily attached to the tool shank or to the workpiece
holding devices. It does not interfere with the cutting operation and thus allows for
continuous monitoring of the tool condition. But due to its high frequency nature and
its sensitivity to micro-structural behavior of material, AE signals often have to be
treated with additional signal processing schemes so that the most useful information
can be extracted.

5) Since AE signals are not influenced by the dynamic characteristics of the machine
tool, implying that such techniques would be readily transferable from one machine
tool to another.
6) AE monitoring has proven to have an advantage over many other techniques because the output acoustic emission signal is directly related to the basic mechanisms of the cutting process [30, 31, 47, 77].

2.5 Data Acquisition:

The layout for the experimental work is shown in fig. 2.7 and Photograph 2.1. Though the literature contains many applications of AE to tool wear monitoring, the signal acquisition set up used and the signal analysis methodology used in this work are different. The AET 5500 AE signal acquisition setup collects analog AE signals from the sensor and the output after suitable processing is presented in digital form i.e., the values of the AE parameters are measured for every second in a cycle and presented as a number, which have been collected and plotted with respect to flank wear value after every two cutting cycles in an experiment.

![Fig. 2.7: Layout of the Experimental Setup](image)

2.5.1 Instrumentation used:

**AET 5500:**

The Babcock & Wilcox AET™ 5500 system (Photograph 2.2) is a PC/AT™ compatible, computer-based, multi-channel acoustic emission data acquisition and processing system. It provides advanced diagnostics for materials, research, design, manufacture, process control and quality assurance. It can be used in a multitude of non-destructive testing applications, in a variety of research and manufacturing environments.
2.1 Acoustic Emission Signal acquisition setup

2.2 Acoustic Emission Signal Analyzer AET 5500
The AET 5500, using a Computer Automation 16-bit microprocessor, detects, monitors and classifies acoustic emission data that result from induced stress relaxation in materials and structures. The AET 5500 accurately measures AE signals produced by materials under induced load and processes this emission data to produce an output based on the specific acoustic emission signal characteristics that the user want to measure and analyze. The system presents this data in a meaningful and usable format on a graphics display. The system also allows the storage of the resultant data for later analysis.

The AET 5500 is a general purpose device that can monitor the type of acoustic emission events described to determine information on material/structural strength and integrity or to locate an acoustic emission source. The AET 5500 can be configured with two to eight channels for monitoring and processing acoustic emission data. To monitor acoustic emissions there is a need for a sensor, which has to be mounted on the material or structure to be tested.

Sensor:- The sensor is a piezoelectric transducer (AC 750, 4525) with a resonant frequency of 750 kHz, which senses the AE wave and converts it into electrical voltage and is sent to the mainframe for processing through a preamplifier.

Preamplifier:- The preamplifiers are cable connected to the sensors to amplify the initial acoustic emission signal before it enters the signal processor. The preamplifier used is a 160 B model, which has a gain of 60 dB and a flat frequency response between 1 kHz to 2 MHz. It has got a filter with a pass band 30 kHz to 2 MHz (wide band).

Cables:- The cables connect the sensor to the preamplifier and the preamplifier to the AET 5500 mainframe. This cable provides power for the preamplifier (from the AET mainframe). It also carries the signal and ground lines.

AET Mainframe:- The AET mainframe, with its 16-bit microprocessor performs all signal processing for the acoustic emission signal. This is the unit into which the signal is directed, via cable, from the sensor and preamplifier. It is a hardware unit that contains various acoustic emission detection and processing modules. The common system modules include the Signal Processing Unit (SPU2) and the optional Voltage Control Gate (VCG) and Audio Unit (AU). The SPU2 is a dual channel, adjustable gain postamplifier that begins the digitization of the acoustic emission signal. Some important
digital modules of the signal processor unit include Ring down Counter / Event duration module (REM), Amplitude / Rise time module (ARM). The REM module provides data such as count rates, number of events, event duration. The ARM module measures peak amplitude of an event, rise time to peak amplitude. The AU is an optional module that can be installed in the AET 5500 mainframe’s front panel, next to the SPU2 modules. This audio unit amplifies acoustic emission preamplifier output signal and heterodynes it into the auditory range.

**AET Intelligent Graphics Terminal (IGT):** The AET 5500 system’s IGT is really a complete microcomputer using the MS-DOS operating system. It shows the desired AE data on the display in a format the user specifies before the test using specific software commands. The IGT has a hard disk drive on which the AE data to be saved can be stored. The IGTs keyboard can be used to enter all of the software commands to setup sensors and displays to monitor measure and show the desired AE data. The IGT connects to the AET mainframe through a high speed 8-bit parallel interface. The IGT does not process any acoustic emission input signals, since all processing occurs in the AET mainframe.

**AET 5500 Software:** The AET 5500 software is the most important component of the system. Using this software the system can be set up to perform various types of tests and process the test data to produce the desired display output [78].

2.5.2 Machine Tool: Vertical Milling Machine:

The face milling operations have been carried out on a Bharat Fritz Werner make vertical milling machine (Photograph 2.3). It has 10 speeds ranging from 56 to 1400 rpm. 9 feeds are available (22.4 to 355 mm/min).

Specifications - Motor – 3 kW, Power supply – 415 V, 3 phase, 50 Hz

2.5.3 Tool makers’ Microscope:

A LABO make tool makers’ microscope is used to measure the flank wear width \( (V_{B_{\text{max}}}) \) (Photograph 2.4). The insert is properly positioned on the microscope and the flank face of the insert is focused using the eyepiece. After the desired view is obtained in
the eyepiece, the two micrometers are used to measure the flank wear width. The eyepiece has a magnification of 15X and the micrometers have a least count of 0.01 mm.

2.6 Experimental Details & Machining conditions

2.6.1 Work piece material details

Three kinds of work piece materials are used for the experimental work.

**Low carbon steel (En-2A)** – Composition – 0.2773 % C, 0.1692 % Si, 0.6812 % Mn, 0.0099 % P, 0.0069 % S
Hardness – 105 RHB

**Medium carbon steel (En-8)** – Composition – 0.4711 % C, 0.3371 % Si, 0.9240 % Mn, 0.0119 % P, 0.0080 % S.
Hardness – 115 RHB.

Grey cast iron – Composition – 3.5 % C

**Workpiece dimension**: 63X140X63 mm

2.6.2 Cutting Tool Details

i) Cutter – WIDAX M650 High shear milling cutter (fig. 2.8)

ii) Cutting tool – Uncoated carbide insert – SEKN 12 03 AFN TTMS grade for steel machining for both rough and finish milling (ISO grade – P15-P30 carbide grades)

SEKN 12 03 AFN THM grade for gray cast iron milling (ISO grade – K10- K20 carbide grades).
2.6.3 Experimental Procedure

Table 2.1 below gives the cutting conditions for carrying out various experiments on all the three work piece materials.

| Cutting Speed (m/min) | 71, 112, 176 |
| Feed (mm/tooth)       | 0.04, 0.06, 0.10, 0.11, 0.16, 0.18, 0.22, 0.25, 0.28, 0.35, 0.4, |
| Depth of cut          | 0.5 mm (constant) |

Experiments have been carried out on Bharat Fritz Werner Vertical milling machine with uncoated carbide inserts. Several trials have been carried out using single insert on all the three work piece materials. Few trials have been carried out using two and three inserts on En-8 steel. The width of the flank wear (VB_max) is measured using the tool maker's microscope.

The AE sensor is fixed on the machine vice side face using a layer of couplant. The couplant is applied mainly to ensure good contact on microscopic level, the two surfaces. A semi-solid gel has been used as a couplant, which helps to transmit the AE waves from the surface of the structure. A pencil lead break test has been carried out to calibrate the sensor. Electrical signals produced by the transducer are first amplified with a preamplifier of 60 dB gain. The detected signals are then filtered by a band-pass filter, to eliminate noise and other extraneous disturbances.

The threshold voltage has been set for measuring various AE signal parameters to carry out meaningful AE signal analysis using the following procedure – the threshold voltage is set to 1.00 V (automatic) using the AET software command. The patented automatic threshold lets the threshold level increase and decrease in response to changing levels of background noise to insure the recording of significant acoustic emission events only. Also the gain switch is adjusted during the milling operation until the event indicator LED starts flashing, indicating that an event is being processed. AE data that are required for the sake of analysis are set using the AET software commands. The conditioned AE signals are then recorded in the IGT memory for future analysis [78].
Appendix 1 gives the various AE parameter values for different conditions.

2.7 Results and Discussion:
I. Single insert experiment –
   1) En-2A steel - Cutting speed: 112 m/min, feed/tooth 0.13 mm

   Fig. 2.9.1 shows the behavior of flank wear with cutting time. The behavior indicates an initial rapid increase in wear, followed by a steady wear pattern and again a rapid increase, when the wear crosses the critical wear value. In this investigation, critical wear value is taken as 0.4 mm both for single and multi-insert experiments. This is similar to the standard flank wear vs cutting time behavior exhibited by cutting tools in continuous machining. The correlation between various AE parameters and flank wear is established in the figures and explanation presented next.

   Fig. 2.9.2 shows the variation of ring down count with flank wear. Ring down count increases initially rapidly and then drops down and then increases. The initial increase is attributed to the micro-fracturing that takes place, when the insert comes in contact with the workpiece. The micro unevenness on the cutting edge of the insert breaks away and produces more of burst emissions. As machining progresses, there will be normal metal removal and more of continuous emissions are produced as there is more plastic deformation. But as machining continues, the flank face of the insert comes in contact with the newly machined work piece surface and there will be rubbing and friction between the two and this leads to the development of flank wear. As machining progresses, there will be more rubbing and more friction and increase in wear. This leads to generation of more burst emissions. Thus in the later stage of milling, as flank wear increases, there is an increase in the ring down count. There is similarity between the behavior exhibited by ring down count and flank wear [51].

   Fig. 2.9.3 shows the variation of rise time with flank wear. This shows a similar behavior as that of ring down count.

   Fig. 2.9.4 shows the variation of RMS voltage with flank wear. There is an increasing trend in proportion to the amount of flank wear. The RMS voltage drops and
Single insert, En-2a, C.speed : 112 m/min, Feed : 0.13 mm/tooth

Fig. 2.9.1 Flank wear vs cutting time

Fig. 2.9.2 Ring down count vs flank wear

Fig. 2.9.3 Rise time vs flank wear

Fig. 2.9.4 Rms voltage vs flank wear

Fig. 2.9.5 Energy vs flank wear

Fig. 2.9.6 Event duration vs flank wear

Fig. 2.9.7 Mean rise time vs flank wear
then increases with the growth of flank wear, beyond the critical wear and then drops. This is because the contact surface area of the tool tip and the workpiece affects the RMS voltage level. In general it is expected that flank wear and notch wear will increase the area of contact in the tertiary zone and hence will increase the RMS voltage [4].

Fig.2.9.5, 2.9.6 & 2.9.7 show the variation of energy, event duration and mean rise time with flank wear. All the AE parameters show an increasing trend with increase in wear and are able to demarcate normal state (wear<=0.4 mm) from abnormal state.

Cutting Speed  70.4 m/min, feed/tooth  0.40 mm

Fig. 2.9.8 shows the variation of flank wear with cutting time. Fig. 2.9.9, 2.9.10, 2.9.11, 2.9.12, 2.9.13 & 2.9.14 show the variation of ring down count, rise time, RMS voltage, energy, event duration & mean rise time. In comparison with the results presented before, it is clear that as the cutting speed increases, the AE parameters are also found to increase. All the parameters show an increasing trend with the flank wear and there is a sudden increase, beyond the critical wear, thereby distinguishing the two wear states. The flank wear vs cutting time curve, do not show all the three zones clearly, instead there is an increasing trend. Beyond the critical wear, all the parameters show lot of fluctuations. The change in the behavior could be attributed to the lower cutting speed and higher feed. The influence of feed rate on the RMS voltage is highly affected by the cutting speed [9].

2) En-8 steel - Cutting speed 176 m/min, feed/tooth 0.22 mm

Fig. 2.9.15 shows the wear pattern. The pattern indicate high wear rate initially followed by steady wear indicating uniform machining, followed by a rapid increase due to more rubbing and friction.

Fig. 2.9.16 show the variation of ring down count with flank wear. Initially ring down count increases rapidly and then drops down and remain almost stable and then increases. The reasons for the same are described before. In addition to these sources, the tool entry and exit during the cut, chip thickness variation generates burst emissions. This
Fig. 2.9.8 Flank wear vs cutting time

Fig. 2.9.9 Ring down count vs flank wear

Fig. 2.9.10 Rise time vs flank wear

Fig. 2.9.11 Rms voltage vs flank wear

Fig. 2.9.12 Energy vs flank wear

Fig. 2.9.13 Event duration vs flank wear

Fig. 2.9.14 Mean rise time vs flank wear
SINGLE INSERT, En-8, SPEED : 176 m/min, FEED : 0.22mm/tooth

Fig. 2.9.15 Flank wear vs cutting time

Fig. 2.9.16 Ring down count vs flank wear

Fig. 2.9.17 Rise time vs flank wear

Fig. 2.9.18 Rms voltage vs flank wear

Fig. 2.9.19 Energy vs flank wear

Fig. 2.9.20 Event duration vs flank wear

Fig. 2.9.21 Mean rise time vs flank wear
causes an overall increase in the ring down count values. Thus there is a similarity in the behavior of this parameter with variation of flank wear.

Fig. 2.9.18 shows the variation of RMS voltage with flank wear. There is an increase in the voltage level in proportion to the amount of flank wear. Fig. 2.9.17, 2.9.19, 2.9.20 & 2.9.21 show the variation of rise time, energy, event duration & mean rise time with flank wear. The rise time drops suddenly for a wear value of about 0.2 mm, beyond which it increases. All the parameters are almost clear in separating the two wear states.

3) Grey cast iron - C.speed 112 m/min, feed/tooth 0.35 mm

Fig. 2.9.22 shows the variation of flank wear with cutting time. The wear behavior is not clearly showing all the three stages. Beyond about 0.2 mm, there is a sudden increase till 0.4 mm, beyond which the flank wear increases linearly.

Fig. 2.9.23, 2.9.24, 2.9.25, 2.9.26, 2.9.27 & 2.9.28 show the variation of ring down count, rise time, RMS voltage, energy, event duration and mean rise time. In case of grey cast iron machining, the chip generation mechanism is different and discontinuous chips are produced, with less plastic deformation. Hence more of burst emissions are produced, since chips are produced by fracture. The wear mechanism is slightly different from that of machining a ductile material like steel. There are more inclusions in the material, which can cause the tool to be subjected to micro-impacts, and also more friction there by causing the tool to fail faster. The parameters show lot of fluctuation because of all these reasons. The experiments have been conducted much beyond the critical wear, till the flank wear reached about 1 mm. The parameters show an increasing trend beyond the critical wear.

II. Two Inserts Experiment:

En-8 steel - Cutting speed 176 m/min, feed/tooth 0.11 mm

For the sake of analysis of AE signals using two inserts during milling, two arrangements have been considered - inserts placed adjacent to each other and inserts placed opposite to each other.
SINGLE INSERT, GREY CAST IRON, SPEED: 112 m/min, FEED : 0.35 mm/tooth

Fig. 2.9.22 Flank wear vs cutting time

Fig. 2.9.23 Ring down count vs flank wear

Fig. 2.9.24 Rise time vs flank wear

Fig. 2.9.25 RMS voltage vs flank wear

Fig. 2.9.26 Energy vs flank wear

Fig. 2.9.27 Event duration vs flank wear

Fig. 2.9.28 Mean rise time vs flank wear
Inserts placed adjacent to each other—

Fig. 2.10.1 shows the behavior of average flank wear with cutting time. Fig. 2.10.2 shows the flank wear behavior for individual inserts. Since the wear undergone by both the inserts is almost very similar, average flank wear has been considered.

Fig. 2.10.3 & 2.10.4 show the variation of ring down count and rise time with average flank wear. Fig. 2.10.5 & 2.10.6 show the variation of RMS voltage and energy with average flank wear. Fig. 2.10.7 & 2.10.8 show the variation of event duration and mean rise time with average flank wear. All the parameters very clearly follow the behavior exhibited by avg. flank wear with cutting time.

Inserts placed opposite to each other—

Fig. 2.10.9 shows the behavior of average flank wear with cutting time. Fig. 2.10.10 shows the flank wear behavior for individual inserts. Fig. 2.10.11 & 2.10.12 show the variation of ring down count and rise time with average flank wear. Fig. 2.10.13 shows the variation of RMS voltage with average flank wear. RMS voltage clearly distinguishes between the two states of tool wear. Fig. 2.10.14 & 2.10.15 show the variation of energy and event duration. Fig. 2.10.16 shows the variation of mean rise time with flank wear. The parameters exhibit an increasing trend, with increase in avg. flank wear.

In multi-tooth milling, each insert cuts different chip thicknesses simultaneously depending on the radial depth of cut. Inserts placed adjacent to each other undergo wear faster, when compared to inserts placed opposite to each other. The values of ring down count and RMS voltage corresponding to critical wear value for adjacent arrangement is more than that for opposite arrangement. In case of inserts placed opposite to each other, ring down count and RMS voltage are clear in distinguishing the normal state from the abnormal state. Also in the low speed, low feed region, AE RMS voltage is seen to increase as the number of inserts increases. But in the high speed region, the effect of number of inserts on the RMS voltage is less obvious [53].
TWO INSERTS (ADJACENT), En-8. SPEED: 176 m/min, FEED : 0.11 mm/tooth

![Graphs showing various measurements vs average flank wear.](image-url)
TWO INSERTS (OPPOSITE), En-8. SPEED: 176m/min, FEED: 0.11 mm/tooth

Fig. 2.10.9 Avg. flank wear vs cutting time

Fig. 2.10.10 Flank wear vs cutting time

Fig. 2.10.11 Ring down count vs avg. flank wear

Fig. 2.10.12 Rise time vs avg. flank wear

Fig. 2.10.13 Rms voltage vs avg. flank wear

Fig. 2.10.14 Energy vs avg. flank wear

Fig. 2.10.15 Event duration vs avg. flank wear

Fig. 2.10.16 Mean rise time vs avg. flank wear
III. Three inserts experiment –
En-8 steel - Cutting Speed 176 m/min, feed/tooth 0.07 mm

Fig. 2.11.1 & 2.11.2 show the flank wear behavior for individual inserts and the average flank wear respectively. It is clear from the figure that the wear undergone by all the three inserts is almost similar. Hence average flank wear has been considered for analysis.

Fig. 2.11.3 & 2.11.4 show the variation of ring down count and rise time with average flank wear. Fig. 2.11.5 & 2.11.6 show the variation of RMS voltage and energy with avg. flank wear. Fig. 2.11.7 & 2.11.8 show the variation of event duration and mean rise time with flank wear. The values of the AE parameters are higher when compared to single and two inserts, as there are more AE sources (based on the AE generation model described by Diei & Dornfeld (1987)). There is lot of fluctuation exhibited by the various AE parameters. As the number of inserts in the milling cutter increases, the possible sources of AE increase and the contribution made by each insert to the total AE generation process is difficult to separate. The inserts have been arranged inside the cutter at equal spacing (120° apart). The ring down count value corresponding to that of the critical wear value is lesser when compared to that of single insert. RMS voltage shows a decreasing trend with the increase in flank wear [58].

IV. Cumulative AE count – En-8 steel

In contrast to the instantaneous values of the ring down count, which is a random variable, the cumulative count seems to show a definite trend. It has been reported by Sampath & Vajpayee(1987) that the cumulative AE counts has a better correlation with progressive tool wear. The nature of acoustic emission in metal cutting has been found to be stochastic and each observation of the count is an independent discrete random variable [47]. Hence cumulative AE count has been considered and it has been plotted against flank wear. The study has been done for single, two and three inserts.

Fig. 2.12.1 shows the cumulative count vs flank wear for one insert experiment, fig. 2.12.2 shows the same for two insert experiment and fig. 2.12.3 shows for three insert experiment. All the three plots show an increasing trend and hence cumulative count can
THREE INSERTS  
CUTTING SPEED: 176 m/min  
FEED: 0.07 mm/tooth

Fig. 2.11.1 Flank wear vs Cutting time

Fig. 2.11.2 Avg. flank wear vs cutting time

Fig. 2.11.3 Ring down count vs avg. flank wear

Fig. 2.11.4 Rise time vs avg. flank wear

Fig. 2.11.5 Rms voltage vs Avg. flank wear

Fig. 2.11.6 Energy vs Avg. flank wear

Fig. 2.11.7 Event duration vs Avg. flank wear

Fig. 2.11.8 Mean rise time vs Avg. flank wear
Cumulative AE count for one, two and three inserts

Fig. 2.12.1 Cumulative AE count vs flank wear (for one insert)
C.speed 176 m/min, feed 0.22 mm/tooth

Fig. 2.12.2 Cumulative AE count vs flank wear (for two inserts)
C.speed 176 m/min, feed 0.11 mm/tooth

Fig. 2.12.3 Cumulative AE count vs Flank wear (for three inserts)
C.speed 176 m/min, feed 0.07 mm/tooth
be used as an effective indicator for monitoring the status of the tool. In case of single and two inserts it is not able to very clearly demarcate the normal state from the abnormal. There is almost a linear relationship. But in case of three inserts, there is a definite trend and the value corresponding to critical wear is around $1.12 \times 10^7$. In case of single insert experiment, the cumulative count value that signifies the tool entering into the abnormal state is around $6.7 \times 10^6$. Thus AE cumulative count has a very good correlation with flank wear [55].

2.8 Conclusions

The conclusions drawn from the experimental studies carried out on three work piece materials using one, two and three inserts in the cutter are presented below.

1) AE parameters are found to be sensitive to the status of the tool. The analysis of the tool wear in this study has been done considering only two states namely normal (flank wear $\leq 0.4$ mm) and abnormal (flank wear $> 0.4$ mm).

2) Ring down count and RMS voltage have been found to be the most sensitive to the tool wear status, when compared to other parameters. But as the number of inserts increased beyond two, the analysis becomes more difficult.

3) RMS voltage is very clear in distinguishing the normal state from the abnormal state of the tool. This is because of an increase in the RMS voltage with increase in flank wear, beyond the critical wear, except in the case of three inserts.

4) As cutting speed increases, ring down count, rise time and RMS voltage increase with increase in the number of inserts. AE parameters are most sensitive to cutting speed, followed by feed. Depth of cut has no influence on the AE parameters, and hence it is kept constant at 0.5 mm.

5) The values of AE parameters are comparatively higher in case of two and three insert experiments when compared to one insert experiments. This is because of multiple sources of AE during milling.

6) Cumulative AE count has been found to have a good correlation with progressive wear. The nature of AE in metal cutting is found to be stochastic and each observation of the ring down count is an independent discrete random variable.
2.9 Limitations

1. The application of AE to milling is less straightforward. The difficulty in applying AE signal analysis to the milling process is that pulse shock loading occurs during the entry and exit of each individual tooth into the workpiece. It is possible that the magnitude of these shock pulses is equivalent to those generated during fractures. It is clear that AE based monitoring methods may be successfully applied in the monitoring of continuous processes, the discontinuous nature and process variability associated with milling cause limitations in its application. This can be overcome to some extent by using sensor fusion i.e. using AE and any other signal like force or vibration [41].

2. The study has been carried out on three classes of workpiece materials namely En-2a steel, En-8 steel and grey cast iron, for a limited number of cutting conditions. The number of experiments carried out using two and three inserts are limited, as they have been carried out only to make a comparative evaluation with the results obtained using one insert. The study has not been carried out under controlled conditions. The conclusions drawn from this study are generally applicable for any workpiece material-tool combination and any cutting conditions, particularly for single insert. But for two and three inserts, the conclusions drawn from this study hold good for the workpiece materials and cutting conditions used in this work. There is a need to improve the method of signal collection, as the sensor has been mounted on the machine vice, as closer and at the same time at a safer distance from the machining process. Hence there is a possibility that some of the useful signals may be lost and may have an impact on the interpretation of the results obtained.