Optimization of Offset Operation in MicroTurn CNC Machine

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Abstract— The research is to reduce the frequent offset problem in cnc machine during turning operation. The offset problem is occurred mainly due to tool wear rate. This paper reviews briefly the research of sensing of tool wear condition in turning. The two methods, trial and error method and the acoustic emission sensor method are used to sense the tool wear rate and reduce the frequent offset problem in cnc machine.

Previous research has shown that acoustic emission (AE) is sensitive to tool wear. However, AE, as a monitoring technique, is still not widely adopted by industry. This is because it is as yet impossible to achieve repeatable measurements of AE. The variability is due to inconsistent coupling of the sensor with structures and the fact that the tool structure may have different geometry and material property. Calibration is therefore required so that the extent of variability becomes quantifiable, and hence accounted for or removed altogether. Proper calibration needs a well-defined and repeatable AE source.

In this research, various artificial sources were reviewed in order to assess their suitability as an AE calibration source for the single-point machining process. Two artificial sources were selected for studying in detail. These are an air jet and a pulsed laser; the former produces continuous-type AE and the latter burst type AE. Since the air jet source has a power spectrum resembling closely the AE produced from single-point machining and since it is readily available in a machine shop, not to mention its relative safety compared to laser, an air-jet source is a more appealing choice.

Index Terms— offset ,. tool wear rate, acoustic emission sensor , quantifiable, single-point machining

1. INTRODUCTION

The calibration procedure involves setting up an air jet at a fixed stand-off distance from the top rake of the tool tip, applying in sequence a set of increasing pressures and measuring the corresponding AE. It was found that the root-mean-square value of the AE obtained is linearly proportional to the pressure applied. Thus, irrespective of the layout of the sensor and AE source in a tool structure, AE can be expressed in terms of the common currency of 'pressure' using the calibration curve produced for that particular layout. Tool wear stages can then be defined in terms of the 'pressure' levels. .

Metal cutting is a metal removal process. There is a wide variety of cutting operations of which the three most widely used are turning, milling and drilling. In this research, flank wear in turning was studied. In turning, a single-point tool is used remove unwanted work material to produce a surface of revolution. The machine tool on which this is accomplished is called the lathe.

All cutting tools wear during machining and continue to do so until they come to the end of their tool life. The life of a tool refers to the productive time available for machining that will generate surface texture and work piece geometry accuracy of an acceptable quality. In each cutting operation, the choice of tool material and tool shape is based on not just cost but also on the wear and failure resistance of the tool. Most tools fail either by fracturing or by gradual wear. The two main types of gradual wear are flank wear and crater wear, both resulting from the effect of sliding friction. Flank wear occurs on the side face of the tool that rubs against the machined work surface and crater wear on the top face over which the chip slides.

Dan (1990) reported that tool failure contributed on average up to 6.8% of the downtime of machining centres. Tool wear or failure may damage the tool holder, workpiece or machine leading to total disruption of the manufacturing system and may even cause injury to the machine.

In machining, whether a tool needs to be changed is decided either by a machine operator performing a visual inspection of the tool or by prediction based on its life expectancy. Visual inspection of the tool condition or machined finish requires a certain level of experience. The decision based on tool-life expectancy suggests the idea of a shortest life for a class of tools calculated from previous data. For a particular machining condition, the tool manufacturer gives a recommended tool life for a certain insert. The practice of tool replacement based on fixed tool life may not be the most economical since a tool can be replaced prematurely or only after damage has been done. Consequently, besides the unnecessary wastage of some tools, frequent tool changes incur higher machine downtime, decreasing thereby the system productivity and increasing production costs.

In an increasingly competitive global market, manufacturing companies are put under pressure to achieve continual efficiency gains by reducing cost and improving product quality. Advances in manufacturing technology in the form of machining centres have facilitated these gains; but because of the high capital investment involved, machining centres need to be run at peak efficiency and therefore be maintained to be in perfect condition. Traditional maintenance policies, such as fixed-time preventive maintenance, not to mention 'run-to-failure', are unable to deliver the kind of maintenance required for these machining centres; condition monitoring appears to provide the only sensible alternative.

Investigations into sensitive methods of measuring tool life and assessing tool damage have been done for two main potential advantages. Cost can be reduced by implementing on-line tool failure detection; the fact that tool conditions can be correctly identified means that the number of scrapped items is minimised while product quality is improved.

Reliable on-line tool monitoring to provide information on the exact time of tool change is undoubtedly desirable. Various techniques for tool wear monitoring have been studied over the past few decades. However, most of them only work under strictly specified ranges of operating condition. The main reason is that the mechanism of tool wear is complex and depends on a host of factors, for example, the material properties of the cutting tool and workpiece, tool geometry and cutting conditions. Thus, data features extracted from a sensor

may be incomplete and hence unlikely to give a unique interpretation of the tool condition. Multi-sensor data fusion is more likely to be the answer.

Data fusion refers with the combination of data from multiple sensors into one coherent and consistent internal representation. The sensor data sets may be of the same or different data types. In this research, both acoustic emission and acceleration sensors were used and the corresponding types of data are different. Together, they would provide a complementary view of the state of the cutting tool and the data features can be used to synthesise inferences that are impossible to make based on an individual sensor alone. In addition, since two accelerometers were used, producing competitive data sets about the same characteristics of the environment, they would reduce the uncertainty in the fused inference.

1.1. Acoustic Emission And Vibration For Tool Wear Detection

Acoustic emission (AE) is the phenomenon of transient elastic waves produced by rapid release of energy within a material [McIntire (1987)]. Minute displacements resulting from these waves as small as 10-14 meter can be detected. There is a great amount of research literature on AE and a sizeable proportion is on AE applied to tool wear monitoring with encouraging results reported. However, AE as a technique suffers from one fundamental problem: data obtained under apparently identical conditions is often non-repeatable. This fact makes knowledge transfer from one system to another very difficult. The main causes of the inconsistency problem are due to:

1) The interfacial coupling condition between the sensor and the tool.

2) The interfacial coupling condition between the tool tip insert and the tool holder.

3) The difference in the spatial locations of the AE source and the sensor and in the nature of the signal propagation path.

In this research, a study was attempted to minimise the effects on the measured data of the three causes mentioned above. An artificial source, the air jet, was used to calibrate the tool system.

As mentioned earlier, vibration signals were also used in conjunction with the AE signal for detecting tool wear. A coherence function was established between the two acceleration signals in the feed force and tangential force directions. By virtue of its definition, the coherence function can only assume a range of values from zero, and when to one. The theory postulated is that when the two forces are completely uncorrelated, the coherence function is zero, and when the two forces are completely correlated, its value is unity. Values of the coherence function at around the natural frequency (5 kHz approximately) of the tool and at the high frequency range (18 — 25kHz) were used to obtain inferences on the state of tool wear.

1.2 Aim & Methodology

This research is to develop an intelligent on-line tool wear condition monitoring system for single point turning operations using acoustic emission and vibration.

There are three main aims, listed below:

1. To establish a methodology for calibrating the acoustic emission (AE) signal produced in single-point machining. This refers to the calibration of the whole tool system from the location of the source, through the signal propagating medium, to the AE sensor itself.

2. To provide accurate and reliable inferences on the stages of tool wear. The root mean-square of AE and the vibration signals will be studied, and the data features extracted from these signals will be related to the flank wear on a carbide tool tip. Flank wear is used as the measure of the wear condition of the tool.

3. To design and test an expert system, also known as the belief network, to perform the necessary work of fusing data features from AE and acceleration and of making inferences on tool wear.

Calibration of AE systems allows different sensor data to be converted to a common reference, alleviating the variability caused by interfacial and structural variations. Research results in terms of calibrated AE are therefore readily transferable.

1.3. Objectives Of Research

In order to achieve the aims of the project, the following tasks need to be performed:

(1) Reviewing Up-To-Date Literature

Review of other researchers' findings and relevant theories are conducted in order to:

• Understand the types of tool wear in metal cutting and the background theory of metal cutting.

• Understand the theories and techniques of AE and vibration, their advantages and disadvantages when applied to tool wear monitoring; find out the AE and vibration parameters which are sensitive to tool wear and select appropriate parameters to be used in this research.

• Study different AE calibration techniques and evaluate the strength and limitations of different artificial AE sources.

• Assess the performance of a small number of diagnostic systems and select one to provide the necessary data feature fusion of AE and vibration signals to draw inferences on the stage of tool wear.

2) Studying Available AE And Vibration Instruments And Techniques

Preliminary tests are to be performed to identify the limitations of implementation. The different methods are to be investigated for measuring flank wear and for providing a record of the wear area. An air jet source and a pencil lead breakage source are to be investigated with regard to their possibility to be used as calibration sources.

(3) Selecting A Suitable Artificial Ae Source For Tool Wear Monitoring

In order to calibrate a tool system, a repeatable artificial AE source is needed. Comparison of artificial AE sources is to be conducted based on the bandwidth, shape and size of the signal spectrum. A pulsed laser source and an air jet source are to be compared against AE obtained from machining.

(4) Establishing The Methodology For Calibrating A Tool System Using An Air Jet As The Ae Artificial Source

The effect of clamping torque on the AE signal is to be studied. The clamping torque is the torque used to fasten a tool insert to its tool holder. Calibration curves of the air jet source are to be produced experimentally that relate the air jet pressure to the AE signal generated for two different transducers at two different locations. Results from the different set-ups are then compared.

(5) Proving the linearity of the tool system for AE Transmission

The AE produced from machining is much stronger than that from the air jet. Experiments are to be performed in order to decide if AE from these two sources are similar and to verify that the tool system is linear.

(6) Determining The Accuracy Of System Transferability

The AE signals from the two different sensors at different locations are to be converted to the equivalent pressure values. Machining at three different cutting conditions is to be performed in order to determine the degree of transferability of AE equivalent pressure values obtained form the two sensors using the Pearson correlation coefficient. (This is presented in Chapter 5.)

(7) Presenting The Theory Of The Coherence Function For Tool Wear Detection

A linear mathematical model is to be developed to explain the relationship between flank wear and the coherence function. This function involves the two acceleration signals in the tangential and feed directions. Certain frequency bands of the coherence function are to be identified that are related to flank wear.

2. LITERATURE REVIEW

In this , the review of literature is divided in to 3 parts: wear in metal cutting, signal processing and classification techniques. In the first part, wear in metal cutting, the basic theories of metal cutting are presented along with a description of tool wear types and mechanisms. In the second part, signal processing, AE and vibration theories and their parameters are explained; previous research by other workers of AE and vibration in the area of tool wear moni-

toring are surveyed; and AE calibration and system calibration techniques to date are reviewed. In the third part, classification techniques, neural networks and belief networks are reviewed.

2.1 Wear In Metal Cutting

Turning is a process using a single point tool that removes unwanted material to produce a surface of revolution. The machine tool on which this is accomplished is called a lathe. The important variables of a cutting condition are the cutting speed, the feed and the depth of cut [Shaw (1984)].

2.1.1 Types Of Cutting Tool Wear Mechanism

Shaw (1984) classified tool wear mechanisms into 3 types: adhesive or attrition wear, abrasive wear, and diffusion wear.

2.1.1.1 Adhesive Wear or Attrition Wear

Adhesive wear or attrition wear occurs mainly at low machining temperatures on the chip face of a tool. This mechanism often leads to the formation of a built-up edge on the cutting edge. Junctions between the chip and tool materials form strong bonds as part of the friction mechanism. If the bonds are stronger than the local strength of the material particle, small fragments of the tool material can be torn out and carried away on the underside of the chip or the new machined surface.

2.1.1.2 Abrasive wear

Abrasive wear is loss of tool material on the tool face. It occurs when hard particles in a chip rub with the tool rake face resulting in tool material being removed. Due to the great hardness of tungsten carbide, abrasive wear is much less likely to be a significant wear process with cemented carbides than with high speed steel.

2.1.1.3 Diffusion wear

Diffusion wear is the wear that occurs at high surface temperature.The chemical properties of the tool-material and the affinity of the tool-material to the work-piece material will decide the development of the diffusion wear mechanism. Hardness of the tool-material will not much effect the process. The metallurgical relationship between the materials will determine the amount of the wear mechanism. Some cutting tool materials are inert against most work-piece materials, while others have high affinity. Tungsten carbide and steel have affinity towards each other leading to the diffusion wear mechanism developing. This results in the formation of a crater on the chip face of the insert. [Model Metal Cutting (1994)]

2.1.2 Types Of Tool Failure

According to Shaw (1984), the sources of tool failure are all the above tool wear types plus the following three additions:
1) Fracture: that occurs more in brittle tools under interrupted cutting conditions.
2) Chipping: that is a small scale crumbling of the cutting edge.
3) Plastic deformation: that is caused by high temperature and high pressure on the cutting edge.

2.1.3 Types Of Tool Wear And Tool Failure In Carbide Cutting Tools

Many types of tool materials have been used such as high speed steel (HSS), tungsten carbide (WC), titanium carbide (TiC). The usefulness of each type of tool material is dependent on many factors such as the relative tool hardness, work material, condition of machine and type of operation. In this research, the cemented-carbide, throw-away tool tip will be studied. Cemented carbide is a powder metallurgical product. These carbides are very hard and the main members of the family are tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC) and niobium carbide (NbC). The binder used is mostly cobalt (Co). Five main types of tool wear and tool failure are explained in the following sections.

2.1.3.1 Flank wear

Flank wear is gradual wear caused by friction between the surface of the material being machined and the tool flank, mainly from the abrasive wear mechanism. Flank wear is sometimes called wear-land wear [Shaw (1984)]. It results in a loss of relief angle on the clearance face of the tool. The wear rate increases rapidly as the cutting speed is increased. Excessive flank wear often leads to poor surface texture, inaccuracy and increasing friction as the edge changes shapes.
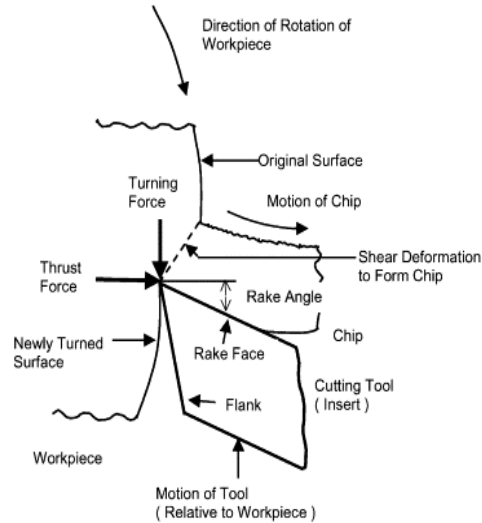
2.1.3.1 Flank wear of carbide tool

2.1.3.2 Crater wear

Crater wear, , is gradual wear on the tool face caused by the friction between the chip and tool face. Crater wear on the chip face can be due to abrasive and diffusion wear. When cutting steel at high speed and feed, diffusion is predominant and a crater is formed on the rake face of the cutting tool. A characteristic form of crater wear is a hollow in the rake face some distance behind the cutting edge. The point of greatest depth usually occurs near the midpoint of the contact length since this is where the tool face temperature is normally maximum.

The volume available to be worn away before total destruction is much greater for crater wear than for wear-land wear. Excessive crater wear changes the geometry of the edge and can deteriorate chip formation, alter the cutting force direction and weaken the edge. Under the very high speed and feed rate, crater wear is the type of wear that determines the life of a tool. But for economic cutting speed conditions, flank wear is usually the controlling factor.

2.1.3.3 Deformation of nose radius

Deformation of the nose radius or plastic deformation under compressive stress is not a wear process since no material is removed from the tool. It takes place as a result of the combined high temperature and high pressure on the cutting edge. It is not usually uniform along the tool edge but often starts at the nose of the tool. In high speed tool steel, forces and temperature may be increased locally and so the flow pattern in the work material is modified.

These more severe conditions bring into play the accelerated wear processes which reduce tool life. In carbide tool steel when the cutting speed or feed are raised, the tool life is often limited by the deformation of the tool under compressive stress on the rake face. Carbide tools can withstand only limited deformation, even at elevated temperature, and cracks form leading to sudden fracture. Figure 2.3 shows such a crack in the rake face of a tool, this surface being stressed in tension as the edge is compressed.

2.1.3.4 Chipping

Chipping is the formation of fragments of the tool material of microscopic size, under conditions where a built-up edge is formed, resulting in fragments being torn from the tool edge. It is a slow wear mechanism with steel tools but may cause rapid wear on carbide tools. Fatigue, arising from cycles of loading and unloading during intermittent cutting, is a frequent cause of this wear type. Figure 2.4 shows the edge chipping of a carbide tool after cutting steel at low speed with a built-up edge.

2.1.3.5 Fracture

Fracture can be the catastrophic end of a cutting edge. It is rare for fracture on a part of the tool edge to occur while it is engaged in continuous cutting. More frequently the tool fractures on starting the cut, particularly if the tool edge comes up against a shoulder so the full feed is engaged suddenly. Interrupted cutting and operations such as milling are particularly severe and may involve fracture due to mechanical fatigue. Fracture may be initiated also by deformation of the tool, followed by crack formation.

2.1.4 Tool Life

The end of a cutting tool's life corresponds to when the tool cannot be used properly in further cutting. The causes of the end of tool life are due to many types of tool wear and tool failure modes mentioned above. A common measure of tool life is the width of the flank wear and sometimes the dimensions of crater wear.

2.2 REVIEW OF AE AND ITS SIGNAL PROCESSING

Acoustic emission is a powerful technique for non-destructive testing and material evaluation. Older NDT techniques such as radiography, ultrasonic, eddy current detect geometric discontinuities by beaming some form of energy into the structure under test. Acoustic emission is different: it detects microscopic movement, not geometric discontinuities.

AE is a passive technique. The growing defect makes its own signal and the signal travels to the detecting sensors. The main benefits of AE compared to other NDT methods are that AE is a real time method and it is less intrusive. The discontinuities of defects can be detected by AE at an early stage when they are occurring or growing. AE techniques can be used as a warning system before the testing material is severely damaged. AE requires access only at sensors: on the other hand most other NDT techniques require access to all regions inspected.

Acoustic emissions, by defmition, are transient elastic waves generated by the rapid release of energy from localised sources within a material [McIntire (1987)]. These elastic waves can be detected by microphones or transducers attached to the surface of the specimen. AE techniques have been used in many applications such as in material degradation, leak and flow, solidification, machining.

In order to detect AE events, a transducer is required to convert the very small surface displacement to a voltage. Displacements as small as 10 -14 metre can be detected by the use of the most sensitive sensors. The most common type of transducers are piezoelectric which are sensitive, easy to apply and cheap. A couplant is needed for good transmission, and is usually achieved by grease or ultrasonic couplant, together with some means of applying force to maintain contact.

There are two types of piezoelectric transducer: resonant transducers and broad-band transducers. The principal or resonant frequency of a piezoelectric element depends on its thickness. The piezoelectric element is unbacked or undamped in a resonant transducer but a broad-band transducer has an element that is backed with an attenuating medium. The frequencies of most AE resonant transducers lie in the range of 100 kHz to 1 MHz. Resonant sensors are more sensitive than broadband types because of the gain provided by mechanical resonance.

Broadband sensors are used when the object of interest is the frequency spectrum of AE but they do not have as high a sensitivity as resonant transducers. Because of the reliance on mechanical resonance, resonant sensors can be used to detect preferentially a frequency range which has been shown from previous experience to give a good indication of the AE changes. Alternatively, a broad-band sensor can be used and the required frequency selected by filters.

Elastic waves emitted from materials can be divided into 2 types based on their appearance: burst and continuous. A burst emission is a signal, oscillatory in shape, whose oscillations have a rapid increase in amplitude from an initial reference level (generally that of the background noise), followed by a decrease (general more gradual) to a value close to the initial level. A continuous emission is a qualitative term applied to acoustic emission when the bursts or pulses are not discernible. (A pulse is an acoustic emission signal that has a rapid increase in amplitude to its maximum value, followed by an immediate return.)

2.2.1   AE WAVEFORM PARAMETERS
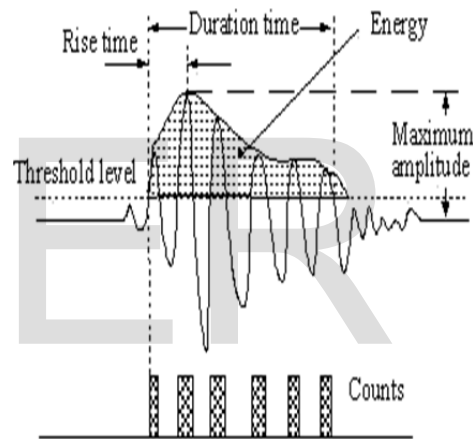
2.2.1Acoustic wave form

1) Ring down count

Ring down count is the number of times a signal exceeds a pre-set threshold. This is a simple measure of the signal size, since larger signals typically give more counts. Electronically this is a very easy measurement, and it was the first to come into widespread use. By summing the counts from all the detected emissions, one has a convenient measure of the total emission from the specimen or structure. The number of counts *(N)* can be calculated by

$$N = W/2_\pi B \ \ln V_o/V_t$$

where

w = angular frequency

B = decay constant(greater than 0)

V_o = initial signal amplitude

V_t = threshold voltage of counter

2) AE rms

AE rms is the root mean squared value of the input signal. Since acoustic emission activity is attributed to the rapid release of energy in a material, the energy content of the acoustic emission signal can be related to this energy release.

3) Signal amplitude

Signal amplitude is the maximum value of amplitude of the received signal. This is an important parameter because it governs the detectability of the

event (detection depends on the amplitude exceeding the pre-set threshold). Like counts, amplitude is a useful measure of the signal size; and it is the appropriate variable to use for attenuation measurements.

4) Duration

Duration is the time between the point at which the event first exceeds the threshold and the point at which the event goes below the threshold. This parameter is closely related to the ring down count, but it is used more for discrimination than for the measurement of emission quantities. For example, long duration events (several milliseconds) in composites are a valuable indicator of delamination. Signals from electromagnetic interference typically have very short durations, so the duration parameter can be used to filter them out.

5) Rise time

Rise time is the time between the point at which the event first exceeds the threshold and the point at which the amplitude reaches its peak value. This parameter is useful for source discrimination and signal filtering. It can be used to filter out signals from electromagnetic interference, which usually have very short rise times.

2.2.2 AE WAVE PROPAGATION

The AE waveform detected by a sensor is much more complex in form compared to the AE at source. It is shaped by the propagation effects between the source and sensor. The important factors of wave propagation for AE are wave modes and wave velocity, wave reflection and mode conversion, and attenuation.

2.2.2.1 Wave modes and wave velocity

There are 4 types of modes; compression (longitudinal), shear, surface (Rayleigh) and plate (Lamb). Each mode travels at the different speed depending on the material; and, for Lamb waves, the speed depends on the thickness of material as well. In an infmite medium, the longitudinal wave and the shear wave are the only two wave types that can exist.

The Rayleigh wave exists in a semi-infmite medium and the Lamb wave mode in a finite plate. The velocity varies with frequency, a phenomenon known as velocity dispersion. The compression wave is the fastest. Shear and surface waves travel at approximately 60% and 50% respectively of that of the compression wave. The velocity of Lamb wave varies with frequency and the thickness of the medium.

2.2.2.2 Wave reflection and mode conversion

When a wave strikes an interface or boundary between two materials, the energy is partly reflected and party transmitted. The partition of energy between the transmitted and reflected waves depends on the angle of incidence and on a material property known as the acoustic impedance.

Mode conversion is the conversion of one wave mode into another. Mode conversion can occur only at an interface between two media.

2.2.2.3 Attenuation

Attenuation is the loss of amplitude with distance as the wave travels through a structure. The major causes of attenuation are:

(1) Geometric spreading of the waves by simple geometry and by loss in adjacent media. The amplitude falls off inversely with the distance in three-dimensional media such as concrete blocks, and inversely with the square root of distance in two-dimensional media such as pressure vessel shells (LOCAN 320 User's Manual (1990)). This effect is dominant close to the source.

(2) Absorption or damping in the propagation media. The amplitude falls off exponentially with distance. Attention depends on material and on the operating frequency. The higher the frequency the higher the attenuation rate .

2.2.3 REVIEW OF VARIOUS TECHNIQUES FOR TOOL WEAR DETECTION

In the past two decades many researchers have investigated various techniques for tool condition monitoring. A great majority of them have focused on tool wear monitoring as determined by flank wear and crater wear, rather than plastic deformation, nose radius, chipping and micro fracture. Tool wear sensing can be classified into two major categories, direct and indirect methods [Dan and Mathew (1990)]. The direct method measures the actual tool wear, whilst the indirect method measures a parameter correlated with tool wear. The direct methods are described in the following five sections.

2.2.3.1 Optical measurement

Image analysis with a CCD camera has been used to measure flank wear on a single point cutting tool [Levi et al (1985)]. The flank wear could be seen clearly owing to the higher reflectivity of the worn area compared with the unworn surface. Sata et al (1979) proposed a system comprising a TV camera coupled to a pattern recognition technique to classify the morphology of tool failure. The morphology of wear was compared to the decision table, which had been established by a learning algorithm in advance. Laser light has also been used to illuminate the flank wear of a cutting tool (Jeon and Kim 1988). The image was converted into digital pixels which were then processed to determine the width of the wear land.

2.2.3.2 Wear particle and radioactivity

Uehara (1972) described a system for the detection of tool wear by scanning chips with an electron microprobe analyser. This technique is based on exciting a sample of wear and cutting debris by electron beams rays. The X-ray radiation emitted from them was collected and analysed to find the amount of wear by X-ray spectrometers. Tool wear can also be detected by using abraded radioactive wear particles. In a method reported by Cook (1980), a small amount of radioactive material was attached or implanted to the flank of the tool. The spot was checked at the end of each cutting cycle. If the spot disappeared, the tool would be considered to be worn.

2.2.3.3 Tool/work junction resistance

Uehara (1973) researched into a method relying on detecting resistance at the tool/work junction. A thin film conductor was bonded onto a tool flank. When the tool wears, parts of the conductor also wear. Consequently the resistance to current flow decreased indicating tool wear.

2.2.3.4 Changes in workpiece size

The dimension of a workpiece corresponds to the size of wear. Gomayel and Bregger (1986) used an electromagnetic sensor to measure the change of the diameter. The voltage output obtained from the electromagnetic sensor was directly related to the gap between the sensor and the workpiece, hence the extent of tool wear.

2.2.3.5 Tool/work distance

The distance between a tool holder (or tool post) and a workpiece decreases as the tool wears. The distance can be sensed by using an electronic feeler micrometer mounted on the tool holder or a stylus attached on the tool holder [Suzuki and Weinamann (1985)].Indirect methods measure a parameter that is correlated with tool wear.

2.2.3.6 Cutting forces

The three components of the cutting forces, which are the tangential force, the feed force and the normal force, were found to increase suddenly as a broken tool nose was jammed between the tool and the workpiece; they then consequently dropped to zero because of the gap between the tool and the workpiece as the broken part of the tool insert was released [Tlusty and Andrews (1983)]. By contrast Lan and Dornfeld (1984) observed that the tangential force decreased as an insert broke while the feed force might decrease or increase depending on the degree and type of micro breakage on the cutting edge.

Dimla and Lister (2000) used a tool-post-dynamometer to generate cutting force data in the time domain and frequency domain. They proposed that as the tool wear reached catastrophic failure, amplitudes at certain frequencies correlated well with the dynamic force changes. Lee et al (1992) established the relationship between the dynamic tangential force and flank wear: the amplitude

of the dynamic force increased with tool wear and then decreased just prior to the onset of tool failure. A personal computer was used to automate tool wear detection by setting up two criteria: the threshold value of the percentage drop of the dynamic tangential force from its maximum and the gradient of the curve of the dynamic force with time.

2.2.3.7 Sound

Flank wear on the tool can also be detected using the noise spectra resulting from the rubbing actionof the tool and the workpiece. Sadat et al (1987) found that the noisein the frequency range 2.75 — 3.5 kHz significantly increased from 9 to 24 dB as a sharp tool became worn.

2.2.3.8 Power/motor current

Liao (1974) investigated the relationship between the power or the current of the main drive motor of the spindle and the tool wear and tool breakage. He found that the motor current dropped and then subsequently recovered to a level before the drop as the tool broke. At the constant spindle speed of the cutting condition, the percentage increase of the motor current from the start to the end of the tool life was approximately constant when the same material was machined.

Constantinides and Bennett (1987) measured the spindle motor power from a vertical milling machine as well as the power spectral density. They concluded that the spectral energy fluctuations of the spindle motor power were linearly related it to the tool wear rate and that they were also affected by the cutting condition and tool geometry.

2.2.3.9 Cutting temperature

Colwell (1975), Turkovich and Kramer(1986), Lin (1995) and Radulescu and ICapoor (1994) attempted to measure the cutting tool temperature and related it to the tool wear. The temperature around the cutting tool edges was found to be related to the cutting tool wear and the friction between the chip and cutting tool.

2.2.3.10 Roughness of machined surface

The sharpness of the cutting edge affects the surface roughness of the workpiece. Takeyama et al (1976) observed that a slightest change of the cutting edge due to chipping or wear was detected using a pair of optical reflection systems.

2.2.4. REVIEW OF AE TECHNIQUES FOR TOOL WEAR DETECTION

In the last two decades, many researchers investigated into the use of AE for tool wear and tool failure detection. The effectiveness was established of the acoustic emission based sensing methodologies for machine tool condition monitoring in machining under combination of feed rate, depth of cut and cutting velocity.

Acoustic emission from orthogonal metal cutting has been studied by many researchers experimentally to determine the influence of cutting parameters, and the rake angle of tool insert.

Heiple et al (1991) used AE to monitor single-point tool oblique machining in several materials. Results obtained showed that heat treatments, which increased the strength of 4340 steel, caused the amount of AE produced during machining to increase. Whilst heat treatments increased the strength of Ti-6A1-4V, the amount of AE produced during deformation decreased. If chip deformation was the main source of AE, then the AErms level of both materials should increase. Thus, they concluded that chip deformation is not the major source of AE, but that the sliding friction at the nose and the flank of a tool was the primary source of AE. Changes in the AE signal with tool wear were strongly material dependent. It was observed that AErms sharply increased with cutting speed for all materials, whilst the increase with feed was small and the pattern was similar for all materials, but the AErms produced, being sometimes strong and sometimes weak for different depth of cut, was strongly material dependent.

• Frequency components

Iwata and Moriwaki (1977) found that the frequency components of

AE in turning operations were below 400 kHz. Diniz et al (1992) found that the AErms and its standard deviation in the range of 200 to 300 kHz increased with tool wear and were suitable to be used for monitoring the growth of surface roughness in finishing turning.

• Data classification for tool wear detection

Neural networks were used to diagnose the tool condition given the input data. More than 60 % of reported research used back-propagation techniques. To increase reliability and sensitivity, multi sensor data fusion was used with acoustic emission and cutting force sensor being the most common.

In a turning process, AE sources generated at the edge of the insert propagated through the tool shank to the transducer. The AE arriving at the transducer has a waveform that has been modified by such mechanisms in the propagation medium as:

(1) reflection and mode conversion of waves at a boundary

(2) energy attenuation

(3) velocity dispersion

(4) geometry and material properties of tool holder

(5) coupling interfaces and

These can cause the signal detected by the transducer to change its waveform considerably; such changes are difficult predict theoretically.AE, as a monitoring technique, is still not widely adopted by industry.

This is because it is as yet impossible to achieve repeatable measurements of AE. The variability is due to inconsistent coupling of the sensor and insert with structures. Modern machining uses indexable insert tools. An insert, clamped onto a tool-holder, is used to remove metal and when all its cutting edges are worn, a new insert is substituted.

When monitoring tool wear using AE, the transmission characteristics of the tool between the tool tip and the sensor are exceedingly changeable. Not only is the sensed AE signal dependent on the geometry of the tool structure and the response characteristic of the sensor, it is also influenced by the subtle changes in the sensor and insert couplings with the tool holder, not to mention the effect of tool wear as observed by different researchers. As a result, AE data are hardly comparable between set-ups, making knowledge transfer very difficult, if not impossible. In order to utilise AE to monitor tool wear this problem needs to be solved.

To overcome the problem stated above, some form of calibration needs to be performed in order to establish the relationship between the AE measured by the sensor and the AE produced from a known reference source located on the tool tip.

2.2.8 AE TRANSDUCER CALIBRATION VERSUS SYSTEM CALIBRATION.

The calibration of a sensor is the measurement of its voltage output into an established electrical load for a given input [McIntire (1987)]. Calibration results are usually expressed as a frequency response. The usefulness of the calibration frequency response is that it permits sensitivity comparison and the assurance of repeatability of the transducer. A sensor's response received from a test can be expressed as a frequency response. The calibration results or the frequency response obtained was related to known artificial AE sources and particular types of test block. The test block was a solid object for calibration of the sensor. Steel was normally chosen because it was expected that AE sensors would be used more on steel than any other material. Different types of media, having different acoustic impedance, will give different calibration.

The standard guideline E1106-86 (1992) provides a standard for primary calibration. The procedure involves the use of a step function source pro-

duced by breaking glass capillary tubing with the typical outside diameter of 0.2mm (0.1-0.3nun). The size of the cylindrical steel test block is 0.9m in diameter and 0.43 m tall. The source is at the centre of the top circular face of the steel block. The local transverse displacement due to AE propagation on the test block surface can be measured using a capacitive sensor at a location symmetrical to that of the sensor under test with respect to that of the source. The standard provides the absolute calibration of acoustic emission sensor. The transducer voltage response is determined at discrete frequency intervals of approximately 10 kHz up to 1 MHz. The unit of calibration is voltage per unit of free motion, for example, volts per metre.

2.2.9 ARTIFICIAL SOURCES FOR AE TRANSDUCER CALIBRATION AND AE SYSTEM CALIBRATION

In order to calibrate an AE transducer or AE system, an artificial AE source is needed. Based on the wave shapes, artificial AE sources can be classified into three different categories as:

1) Noise — produced from, for example, helium gas jet impact, fracture of silicon carbide particles, stress corrosion cracking and phase transformation in AU- 47.5% Cd;

2) Continuous waves - generated by exciting piezoelectric, electromagnetic and electro-static devices;

3) Impulses — arising from sparks, breakage of glass capillary, breakage of pencil lead, dropping of a steel ball on a hard surface to produce an impact, point contact resistive heating and laser pulse heating.

In this research a pencil lead breakage, an air jet and a pulsed laser, were evaluated in reference to their suitability as a calibration source for single-point machining and tool wear monitoring.

2.3 VIBRATION SIGNAL PROCESSING

A system is vibrating if it is shaking or moving backwards and forwards in some way subjected to unsteady disturbances, generated by external or internal agencies. The amount and nature of vibration can be assessed using vibration monitoring which is a non-destructive technique. This technique has been used to monitor machines with rotating parts such as bearings or gears successfully. Thus, it is an important technique for condition monitoring.

2.3.1 MACHINE TOOL VIBRATION

In this project, the cause of machine tool vibration generated by flank wears on tool tips was studied. However the flank wear is not the only source of machine tool vibration. Vibration can be categorised as free, forced and self-induced vibration.

2.3.1.1 Free vibration

Free vibration (or random or transient vibration) is normally induced by a shock (or impulsive) loading of the machine tool, for example, the tool striking a hard grain in the work piece. Free vibration always decays, with time, and its rate of decay is dependent on the damping of the machine tool system.

2.3.1.2 Forced vibration

The system may be acted on by an external force, which is often of a repeated type that tends to maintain the oscillation. The motion of this system is a forced vibration. Forced vibration is usually caused by an out-of-balance force, such as produced by unbalanced rotating members, bearing imperfections or misalignments in a machine member, associated with a component integral with the machine tool. Forced vibration sometimes causes a relative oscillation between the tool and workpiece resulting in poor surface finish. Forced vibration in machine tools is also often caused by cyclic variations in the cutting forces. Such variations occur in side or facemilling, where the forcing frequency equals the product of the tool rotational frequency and the number of teeth on the tool.

2.3.1.3 Self-induced vibration

Vibration can occur in machining operations where cyclic variations in the cutting forces are not normally present such as in turning of plain cylindrical workpiece. It is called the self-induced (or self-excited) vibration in which the forces are generated by the machining process itself. The most important type of self-induced vibration is associated with a phenomenon called the regenerative effect. The regenerative effect occurs when a fluctuating force is created by the variation of uncut chip thickness (t). When the effective value of uncut chip thickness increases, the cutting force will be less. The reason is that the effective rake angle increases when t increases. If the energy produced by the fluctuating force is more than the loss of energy due to the damping of the system, then, vibration in the subsequent passes does not diminish. On the contrary, it may increase in magnitude.

2.3.2 VIBRATION TECHNIQUES FOR TOOL WEAR MONITORING

Vibration is a technique that also has been widely used in detecting tool wear. Same as AE sensors, the vibration sensors can also be easily installed on a tool holder. In addition vibration sensors do not have the same stringent coupling requirement as for AE sensors although installation still needs to be properly done. In this research acceleration signals in both feed and tangent directions were investigated. It is proposed that vibration signals vary with tool failure in some frequency ranges. The use of coherence function was an attempt to provide a solution, which is relatively insensitive to the dynamics, and the process variables except tool wear. The approach using coherence function was first investigated by Dong (1987) who observed that the coherence in the frequency range up to 1.5 kHz followed a consistent trend.

Vibration signals have been found to vary with tool wear in some frequency ranges. Weller et al (1982) reported that the total amount of vibration energy in the frequency range of 4-8 kHz increased with flank wear in a wide range of feed, speed and depth of cut. Taglia et al (1976) observed that, the total power of the acceleration signal in the frequency range up to 2.5 kHz increased with wear up to 1.3-1.5 mm, and then fell rapidly back to the values found for little wear.

The coherence function of the accelerations of the tool in the tangential and feed directions was used as a method for tool wear detection by Au and Owen (1992) and Li et al (1997). Li et al (1997) used the coherence function for tool wear and chatter detection in the machining of a nickel-based supper alloy (Incronel 718). He found that as the tool wear progressed, the autospectra of the two accelerations and their coherence function would increase gradually in magnitude around the first natural frequencies of the vibration of the shank. When the tool approached the severe wear stage, the peaks of the coherence function at the first natural frequencies increased rapidly to values close to unity.

Au and Owen (1992) studied the value of coherence function in the frequency range around the resonance region and observed that it fell with progressive tool wear. They also created a mathematical model to explain the relationship between the coherence function and tool wear. Owen and Au (1992) observed that the coherence function in the vicinity of the resonant frequency of the cutting tool was sensitive to tool wear. They used Principal Component Analysis to classify tool wear into two stages: good tool and worn tool for the three cutting conditions- roughing, semiroughing and finishing. Clusters corresponding to the two different tool stages were clearly identifiable.

2.4   CLASSIFICATION TECHNIQUES

There are a number of classification techniques that have been used for condition monitoring. The common ones are neural networks, expert systems and Bayes' rule. In this section, neural networks and Bayes' rule will be presented.

2.4.1 NEURAL NETWORKS

Complex phenomena occur in tool wear monitoring. Consequently the large amount of experimental data in a cutting process are difficult to analyse by humans. In the last decade, neural network has been applied to tool wear monitoring with some success. Of the different configurations, the three-layer feed forward perception network trained via back-propagation is the most common. To assess the performance of a neural network the following factors will be considered:
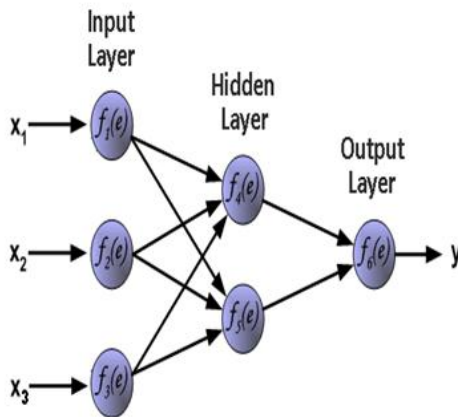
2.4.1 Three layered propagation network

1. Sample mode or batch mode

If several input vectors are to be presented to a network, they may be presented one by one (sample mode) or in a batch (batch mode). Sample mode refers to a single input-output pattern set presented to the neural network. Batch mode occurs when all input-output pattern sets are presented to the neural network in a batch.

2. Training sequence

Training neural network with different training sequences makes a little difference in performance of neural networks.

3. The number of iteration to reach the acceptable value (target minimum error)

4. The number of hidden layers, and the number of neurons in each layer- Any reasonable function can be represented with a two-layer network: a sigmoid layer feeding a linear output layer.

5. Learning rate

Learning rate is measure of the rate of improvement of a backpropagation neural network during training. The training time can be decreased by the use of an adaptive learning step size as large as possible while keeping learning stable.

6. Transfer function

The output of a neuron is dependent on the type of transfer function.

2.4.2 CLASSIFICATION USING BAYES' RULE

In an expert system, named the belief network, was used to create diagrams and predict or classify the stages of tool wear. The belief network (also known as a Bayesian network or probabilistic causal network) captures beliefs between a set of variables which are relevant to some problem.

The advantages of the belief network are its ease of use, user-friendly graphical interface and low cost. The belief network operates on the principle of "Bayes rule" and the "law of total probability of Bayes rule". Before Bayes rule is presented, we shall provide an explanation of concepts such as "the probability of an event", "mutually exclusive or disjoint events" and "conditional probability".

• Probability of an Event

The probability of an event A is a measure of our belief that A will occur. One practical way to interpret this measurement is with the concept of relative fre-

quency defined by

$$p(A)=\lim(frequency/n)$$

where, P(A) is the probability of event A Frequency is the number of times the event A has occurred.

n = the number of repetitions of the experiment

• Mutually Exclusive Events

If the two simple events A and B are mutually exclusive or disjoint (that is to say, when one event occurs, the other cannot), their probabilities must satisfy two conditions.

1. Each probability must lie between 0 and 1.

2. The sum of the probabilities for all simple events (an event that cannot be decomposed) in the sample space equals 1.

3. P(A n B) = 0

4. P(Au B) = P(A) + P(B)

3.0 TOOL WEAR MEASURES AND PRELIMINARY STUDY OF ARTIFICIAL AE SOURCES

In this chapter, preliminary machining tests and their results were presented. Due to the fact that in tool wear monitoring, the AE and vibration parameters chosen have to be reliable, not just in the sense that they are sensitive to tool wear but also in the sense that they are repeatable given the same condition, consideration of the technical capability of the acoustic emission and vibration instruments is necessary.

In addition, the machine tool chosen for the machining tests also needs to be considered. CNC program for machining on a Traub lathe is presented. In order to capture the nature of tool wear, a mould was produced of the tool cutting edge for the different stages of wear and a method, called the replica method, was used. This will be described in this Chapter. Finally, the artificial AE sources used to calibrate the tool system were investigated. The pencil lead breakage and the air jet noise sources evaluated for their repeatability.

3.1   OBJECTIVES   OF PRELIMINARY TEST

The main objectives of the preliminary test are as follows:

1) To measure and eliminate the level of acoustic emission background noise released from the lathe and its surrounding.

2) To understand the use and the limitations of the equipment.

3) To select the proper time interval to record data and measure the progression of tool wear.

4) To choose the type of the tool insert, the workpiece material and the cutting conditions to perform the future test.

5) To find a method to measure accurately the size and progression of tool wear.

3.3   EXPERIMENTAL EQUIPMENT   AND   SPECIFICATION OF THE TOOL TIP AND THE TOOL HOLDER

In this section, the experimental equipment, setting up and specification were presented.

**3.3.1 DETAIL OF THE TOOL TIP AND THE TOOL HOLDER**

Carbide tool tips type GC 4035 DCMT 11 T3 04-UF equivalent to ISO P 35 were used. It is chemical vapour deposition coated carbide (GC 4035) with a thick layer of Al203 on top of medium size of titanium carbides (TIC) or titanium nitrides (TIN). The geometry of the insert is: insert shape 55°, clearance angle 7 0 , rake angle 00, cutting edge length 11 mm. and thickness 3.97 mm. The inserts were clamped on a left-hand tool holder (or tool shank) of type SDJCL 1616H11. The clamping system consists of screw clamp from the top. The tool holder size is 16 mm x 16 mm x 100 mm.

3.3.2 AE EQUIPMENT MODEL 5500

Acoustic emission equipment, the AET 5500, was used. This provides the power to drive an AE preamplifier and transducer. A spectrum analyser was connected to the AET 5500 to perform spectrum analysis on the input AE signal.

3.3.3 AE TRANSDUCER

A broad-band transducer model FC 500 (125 kHz - 2 MHz) was used. This transducer has a calibration curve (sensitivity vs. frequency) which is relatively smooth and flat, in the frequency band 100 kHz to 2 MHz. The placement of the transducer was carefully selected so that the transducer would receive consistent, strong and stable AE signals. It is also essential to hold the transducer securely in place for the duration of the test. The transducer was mounted at the end of the tool holder, 100 mm from the tool tip. Before attaching the transducer, the contacting surface at the end of the tool holder was ground flat. A Silicone Rubber Compound was used to provide the necessary transducer coupling and mounting.
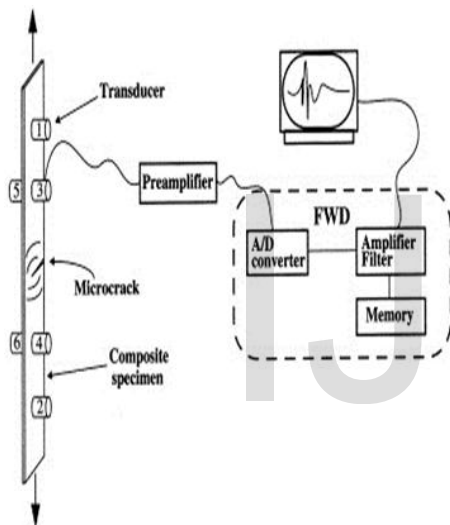
3.3.3 AE TRANSDUCER

3.3.4 AE FILTER AND PRE-AMPLIFIER

A pre-amplifier of 60-dB gain was connected to the AE transducer. The pre-amplifier is placed close to the transducer to amplify the signals. In order to reduce noise, from both mechanical sources and electro magnetic sources, a band pass filter of 125 kHz - 2 MHz was used inside the pre-amplifier.

3.3.5 ACCELEROMETER

For the vibration measurement, two miniature accelerometers were used. Both were mounted close to the tool insert with one in the tangential force direction and the other in the feed force direction. These accelerometers were of type 303A03 driven by a PCB power supply unit. The frequency range of the accelerometer is 1 - 10,000 Hz ($\pm 5\%$) and 0.7 - 20,000 Hz ($\pm 10\%$). The accelerometers are designed for adhesive mounting. As the temperature could be very high during machining, glassceramic- disk insulators, measured 10-mm diameter by 1 mm thick, were inserted between the tool holder and accelerometers. The silicone rubber compound, which can withstand temperature up to 250°C, was used as a couplant at these interfaces. This compound was also used for the AE transducer mounting.

3.3.6 SPECIFICATION OF AE SENSOR

Dynamic:

Peak Sensitivity V/(m/s); [V/µbar] ..... 58 [-62] dB

Operating Frequency Range ....200 - 1000 kHz

Resonant Freq. V/(m/s); [V/µbar] ....200 [800] kHz

Directionality .... ±1.5 dB

Environmental Temperature Range ....-65 to 175ºC

Shock Limit ....500 g

Completely enclosed crystal for RFI/EMI immunity

Physical Dimensions: ......0.75" dia. x 0.84" h (19 x 21.4 mm)

Weight ....32 grams

Case Material ....Stainless Steel

Face Material ....Ceramic

Connector ....SMA

Connector Locations ....Side

Seal..............Epoxy Sensor to Preamp Cable (1 or 2 meters) 1232-X-SMA

3.3.7 HEWLETT PACKARD HP 89410A VECTOR SIGNAL ANALYSER

A two-channel Hewlett Packard HP 89410A Vector Signal Analyser was used to determine the frequency response of AE signal. This Vector Signal Analyser has a bandwidth of 0-10 MHz, which is much more powerful than SI 1220. In order to optimise the measurement resolution, measurement speed and display resolution, the analyser's functions such as resolution bandwidth, frequency span, main length and type of window must be considered (HP 89410A Operator's manual).

3.3.7.1 Resolution bandwidth

Resolution bandwidth is referred to as RBW. This function defmes the analyser's frequency resolution. The maximum frequency resolution obtainable is actually determined by the resolution bandwidth. It may affect how fast the analyser makes a measurement. Usually, resolution *bandwidth* is adjusted automatically as the frequency span is adjusted. Manually selecting a narrow resolution bandwidth can slow down a measurement; on the other hand, selecting a resolution bandwidth that is too wide may not give adequate frequency resolution and can obscure spectral components that are close together.

3.3.7.2 Frequency span

The full-span available for HP 89401A is from 0Hz to 10 MHz. Measurement with spans that start at 0 Hz are often called baseband measurements.

3.3.7.3 Display resolution and frequency span

The number of displayable frequency points (also called number of points, lines or bins) of HP 89410 A, can be selected from 51 to 3201 points of resolution. For a given number of frequency points, narrower spans give finer frequency resolution, because the same number of frequency points represents a smaller range of frequencies. The display resolution can be defined as:

Display resolution = Frequency span/ (Number of frequency points-1)

Display resolution is different from frequency resolution. The frequency resolution bandwidth was determined by the resolution bandwidth. Selecting increasingly narrower spans will improve the display resolution until the point when the maximum resolution available is reached with the current resolution bandwidth setting.

3.3.7.4 Time record length

The time record length (T) depends upon the window bandwidth and the resolution bandwidth, (HP 89410A Operator's Manual) and it is given by

T = WBW /RBW

Where:

WBW- is the window bandwidth which is a constant depending on the window type; and

RBW- is the resolution bandwidth.

However the maximum time record length (T.) is limited by the number of frequency points,

Tmax = (FP -1)/span

Where:

FP is the number of frequency points.

The minimum time record length *(Tmin)* is dependent on the window bandwidth to span ratio.

The reason that window is used in the time domain is to minimise the leakage problem. This problem arises because of the practical requirement that the observation of a signal must be by its very nature within a finite interval. The process of terminating the signal after a finite number of terms is equivalent to multiplying the signal by a window function. A window is a time-domain weighting function applied to the input signal and it can be seen as a filter used to compensate for the fact that most signals are not periodic within the input time record.

Depending on the window shape, the ends of the input time record were attenuated accordingly. The net effect is a distortion of the spectrum. There is a spreading or leakage of the spectral components away from the correct frequency, resulting in an undesirable modification of the total spectrum.

3.3.7.5 Time record size

The time record size (TP), or the number of time points, can be defined as: TP = SR xT

where:

SR is the sample frequency rate.

The sample frequency rate was automatically determined by HP 89410 A and it is 2.56 times of the span (in baseband mode).

4.1.COMPARISON OF ARTIFICIAL ACOUSTIC EMISSION SOURCES AS   CALIBRATION SOURCES

Here two artificial AE sources, an air jet source and a pulsed laser source, were studied in order to assess their suitability as an AE calibration source for the single-point machining process. The effects on the AE were investigated of the clamping torque applied to the tool insert and a calibration procedure was suggested.

Research into the use of acoustic emission (AE) for tool wear monitoring has established that there exists a definite relation between AE and tool wear. Attempts have been made to model the AE process in machining, but despite the fact that general trends could be predicted satisfactorily, the absolute values of AE produced in apparently identical machining processes could still differ markedly from one setup to another.

The root cause of the problem is that the components that make up the AE transmission and measurement system as well as the interfaces between the components are highly variable. For single-point machining, typically, the components comprise an insert, a tool-holder and a sensor whereas the interfaces refer to those that occur between the tool insert and the tool-holder; and between the tool-holder and the sensor. Changes in either the components or the interfaces can produce a very different AE response. A striking example is the coupling between the insert and the tool-holder where, as will be reported in this chapter, an increase in the clamping torque on the insert results in a significant drop in the root-mean-square value of the AE signal (AErms). Consequently, AE results obtained from different research centres are not easy to compare making

knowledge transfer at best difficult, if not impossible.

To achieve transferability of results and hence knowledge, some form of AE calibration is necessary. The process of calibration involves a measurement procedure carried out under specified conditions. Its objective is to establish the relationship between the value of a quantity as indicated by a measuring instrument and the corresponding value from a reference standard. When the result of the measurement can be ultimately related to a stated reference, such as a national or international standard, through an unbroken chain of comparisons all having stated uncertainties, then the measurement is said to be traceable to the standard.

It is important to note that the calibration of a sensor, as is conventionally done, in order to determine the AE at the sensing element of the sensor is not of much practical value. This is because one is often only interested in the character of AE at its source, for example, at the cutting edge in machining. What is immensely more useful is the calibration of the whole AE system with the location of the AE source known and the point of the sensor attachment decided. Understandably, once the layout of the source and sensor is changed, the system has to be calibrated again.

4.2 ARTIFICIAL AE SOURCES FOR TOOL WEAR MONITORING

To qualify as an AE calibration source in tool wear monitoring, the source should possess similar characteristics to the AE sources produced in machining, in addition to the also important characteristic of reproducibility. Here, similarity suggests that the comparing sources have AErms-spectra that closely resemble each other in appearance.

The pulsed laser has been frequently used as an artificial AE source in the past two decades [56-59] for a number of reasons. Firstly, the laser source is broadband and highly reproducible because the pulse parameters can be clearly defined and tightly controlled. Secondly, the energy of a laser pulse is readily quantifiable once the electrical parameters that drive the laser are known. Thirdly, laser can be delivered to remote locations via optical fibres. However, a pulsed laser is not without its drawbacks: it is expensive, requires stringent safety consideration and produces low power, hence weak AE, when, by necessity, operated within the thermo-elastic range so as not to cause damage to the incident surface.

In many respects, an air jet source is similar to the helium jet source. The advantages of the air jet source are that it is non-contact, inexpensive, relatively safe, portable and readily available in a machine shop. The disadvantage is that the behaviour of an air jet in respect of the AE produced is affected by a host of environmental factors such as temperature and humidity.

4.2.1 MACHINING TESTS

Machining tests were performed with the cutting process variables changing as follows:

• Surface cutting speeds from 80 to 150 m/min;
• Feed rates from 0.1 to 0.4 nun/rev; and
• Depths of cut from 0.3 to 1.0 mm.

The work-piece was made from EN24T (0.35-0.45 % carbon) and measured 63.5- mm in diameter by 150 mm in length. Tool inserts of type GC 4035 DCMT 11 T3 04 UF and a tool shank of type SDJCL 1616H 11 (Sandvik Coromant) were used. Details of the insert geometry are: cutting edge length 1 lnun, insert thickness

3.97mm, insert shape 55°, rake angle 0°, clearance angle 7° and nose radius 0.4 mm.

A broad band AE sensor (125 kHz — 2 MHz) was mounted at the end of the tool holder coupled with a silicone rubber compound. The preamplifier was total gain 80 dB with 125 kHz — 2 MHz built in filter. A Hewlett Packard HP 89410A Vector Signal Analyser was used to produce a 401-line AErms-spectrum with frequency from 0 to 1 MHz averaged over 70 consecutive spectra.

4.2.2 AIR JET TESTS

From the preliminary results in Chapter 3, it was shown that the air jet source is a good repeatable source. Hence, the air jet equipment was redesigned to improve the repeatability by replacing parts with their high precision counterparts. A precision filter with a 5 1.tm filter cartridge was used instead. A precision pressure regulator with an operating range of 0.1 to 10 bar was connected to the precision filter. A new digital pressure gauge, with a reading range of 0 to 20 bars, was also added; its resolution is 0.01 bar.

As shown in the block diagram, the air from an air supply passed through an air filter, a precision regulator, a precision pressure gauge, an on/off valve and a nozzle sequentially, emerging as an air jet.
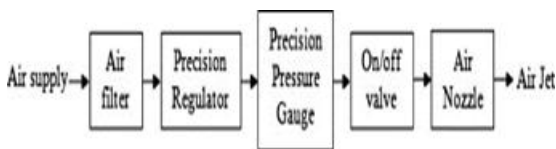
4.2.2 Block diagram of air jet test

The air jet was directed normally at the top rake surface of the insert, 3 mm from the nose tip and equally distant from the leading and trailing edges of the insert.The insert was clamped to the tool-holder with a clamping torque of 2 Nm and the tool holder was, in turn, held in a fixture. Both the stand-off distance from, and the location of the point of impact on, the rake face were controlled by micrometers. The positioning fixture is as shown in Figure 4.3. The measuring instruments and their settings were the same as those for the machining tests but the total gain is 60 dB. Two resolutions of the frequency spectrum were used, namely 401 and 3201 lines.

Tests were performed with two different sizes of nozzle diameters: 1.0 mm and 1.4mm. The stand-off distance was varied from 2 to 16 mm, in increments of 2mm. The air jet pressure was varied between 1 and 5 bars, in increments of 1 bar.

4.3 AE, AIR JET PRESSURE AND INSERT CLAMPING TORQUE

Air jet tests were conducted to study the effects of different sensor location and of different insert clamping torque on the AErms. The tool holder was held in the tool post instead of in the fixture. A new fixture was built to hold the nozzle and to locate the air incident point and the stand-off distance as in Figure 4.15. The air jet equipment and the experimental set-up were shown in Figure 4.16. Similar to the airjet tests in Section 4.2, the air jet was positioned vertically above the top rake face of the insert 2-mm inwards from both the leading and trailing edges of the insert, at a stand-off distance of 5 mm. Three pairs of AE sensors were mounted with the first of each pair on the tool holder and the second on the tool post all held in position using a silicone rubber compound.

These were all PAC sensors and the pairs were: WD and WD with response bandwidth of 100kHz-1MHz, UT1000 and UT1000 with response bandwidth of 60 kHz-1MHz, R30 (100 kHz-400 kHz) and R15 (50kHz- 200kHz). The outputs of these sensors were amplified 60dB and band-pass filtered from 20kHz to 1MHz. The Hewlett Packard HP89410A Vector Signal Analyser was

used to produce an AErms-spectrum with 401-point resolution averaged over 70 successive spectra. The insert was tightened to three levels of torque, namely 0.4 Nm, 1.2 Nm and 2.0 Nm. The air-jet pressure was varied between 3 and 8 bars in 1- bar increments.

5.1 VIBRATION AND COHERENCE FUNCTION

The main difficulty of monitoring tool wear and failure using data features is that these features are often sensitive to cutting conditions such as the feed, speed and depth of cut. In this chapter is presented a theory of tool wear monitoring based on the coherence function of the tool acceleration signals in the tangential and feed directions. The coherence function is believed to be relatively insensitive to the process variables except tool wear. The benefit of the coherence function is that its value is always between 0 to 1, hence providing some degree of normalization, which is particularly beneficial in the situation of turning where the number of combinations of process variables is large.

5.2 MODEL OF CUTTING FORCES AND TOOL

A cutting tool in turning is typically mounted as a cantilever. The dynamic forces that occur during cutting can be resolved into three mutually perpendicular components along the radial, tangential and feed directions referred to respectively

as the x-, y- and z-directions. Since the radial force acting in the x- direction is relatively low compared to the other two forces, the tools tip mainly moves in the yz plane. The dynamic shear force component along the shear plane is resolvable into a y-component and a z-component, and hence they are correlated. On the other hand, the dynamic friction force components that occur at the chip-tool and the tool workpiece interfaces are mainly forces confined in the respective z- and y- directions because of the geometry of the tool and hence largely uncorrelated.

5.3 AE FROM SINGLE-POINT MACHINING

The instrumentation used for the machining tests was identical to that for the air-jet calibration except that the total gain of the sensor output was 34 dB instead of 40 dB. It was necessary to use a lower gain in order to avoid saturation of the signal.

Three sets of machining tests were conducted and their conditions are detailed in the following:

• Machining Test Set 1: Variable feed rates from 0.05 mm/rev to 0.4 mm/rev in increments of 0.05 nun/rev. Cutting speed and depth of cut were constant at 120 m/min and 0.75 mm respectively.

• Machining Test Set 2: Variable speeds from 80 m/min to 150 m/min in increments of 10 m/min. Feed rate and depth of cut were constant at 0.2 mm/rev and 0.75 mm respectively.

• Machining Test Set 3: Variable depths of cut from 0.3 mm to 1.0 mm in increments of 0.1 mm. Cutting speed and feed rate were constant at 120 mm/min and 0.2 mm/rev respectively.

As the preliminary test, the material of the workpiece, measured 63.5 mm in diameter and 150 mm in length, was EN24T with 0.35-0.45 % carbon. All tests were conducted on the Traub lathe.

The ratios of Gy1/Gy2 for the three sets of machining tests were first obtained and then the mean ratio for each set was calculated. It can be observed that these curves match each other very closely.

CONCLUSIONS

The air jet equipment and fixture were developed. The nozzle diame-

ter of 1.0 and 1.4 mm were compared. The 1.0 mm-nozzle was selected to evaluate with the pulsed laser as a calibration source for tool wear monitoring. In terms of the repeatability, the air jet and the pulsed-laser sources have similar variability. The similarity of the air jet and the pulsed-laser sources using the machining AE rms-spectra as the reference are 0.86 and 0.56 respectively. Compared to the pulsed laser, the air jet is more suitable as an artificial calibration source for measuring systems used for machining study and tool wear monitoring. This is because the air jet source has an AE rms- spectrum more similar to that observed in machining than the pulsed laser, is relative safe to use, is less expensive and is more readily available in a workshop.

The relation between the air jet pressure and AE rms at different stand-off distances was established. For a fixed stand-off distance, the AErms of the air-jet increases linearly with the air-jet pressure.

The effect of the clamping torque applied to the insert on the AE signal was

investigated. The clamping torque can affect the AErms if the torque value is low;

but when the clamping torque exceeds 1.2 Nm, the AErms remains constant. (Above 1.2 Nm, the variability of the ratios of AErms between different pairs of sensors relatively decrease.) A safe clamping torque for the tool holder used in this research is around 2 Nm beyond which there is the risk of damaging the hexagonal head of the tightening screw.

1. The methodology for calibrating the acoustic emission signal for the whole tool system was established using the air jet as the calibration source. The AE obtained from different set-ups can be compared in terms of the equivalent pressure.

2. The reliable inferences on the various stages of tool wear were investigated. AE rms and the coherence function were extracted from the raw AE and vibration signal and related to the flank wear on a carbide tool tip.

3. The belief network was designed and tested using fused data from AE and acceleration and inferences on tool wear were made. Acoustic emission measurements can be made transferable using the air jet calibration source. However, recalibration is needed whenever a new insert is used. The system provides real-time condition monitoring at a reasonably low cost, and it does not rely on the experience of the operator.

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