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LATHE STABILITY CHARTS VIA ACOUSTIC EMISSION MONITORING

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ABSTRACT: *Signal parameters characterizing acoustic emission (AE) detected during metal cutting have been theoretically correlated in a simple manner, to the work material properties, cutting conditions, and tool geometry. During chatter, the cutting conditions and the tool geometry change considerably. Self-exited chatter, an instability of the cutting process in combination with the machine structure, is a basic performance limitation of machine tools. In the research findings presented in this paper, changes occurring to AE signal parameters have been used to detect the onset of chatter and hence plot stability charts, during a turning operation. Apart from showing the borderlines of stability, such charts can be used to identify the necessary changes required to eliminate chatter at minimum or no loss of production. The signal parameters investigated include AE mean intensity level, the skew and kurtosis of the power spectrum; as well as the count rate of the emissions.*

NOTATIONS

α	Clearance angle	M_ε	Equivalent mass of a system	x	Displacement
ϕ	Shear angle	N	Number of AE counts	$\dot{x}$	First derivative of x with respect to time
γ	Rake angle	R_a	Arithmetic mean roughness value	$\ddot{x}$	Second derivat respect to time
δ_c	Work surface slope	R_{max}	Maximum peak-valley roughness value	A/D	Analog to digital converter
$\dot{\varepsilon}$	Strain rate	r_ε	Nose radius	AE	Acoustic emission
υ'	Apparent linear frequency	S_ε	Equivalent spring constant	$\overline{AE}$	Acoustic emission mean intensity level
σ'	Principal stress deviator	t	Chip thickness	AR	Auto-regressive
τ_k	Shear strength of material	t_1	Uncut (undeformed) chip thickness	B.u.e	Built-up edge
C_d	Damping coefficient	t'	Width of cut	HF	High frequency
$\dot{E}$	Energy rate	T	Time	MCS	Medium carbon steel
f	Feed rate	U	Cutting velocity	MS	Mild steel
F	Force	U_c	Chip velocity	SS	Stainless steel
h	Depth of cut	U_s	Shear velocity	RMS	Root-mean-square
l	Chip-tool contact length	V	Volume undergoing deformation	RMSv	Root-mean-square voltage
l_1	Length of the sticking zone of the chip-tool face interface	V_s	Threshold voltage		
l_b	Length of tool flank-workpiece interface	$\dot{W}$	Work rate		

INTRODUCTION

Chatter in a turning operation is highly undersirable because it affects the quality of machined surfaces, and also causes both adverse changes in working geometry as well as high rates of wear of cutting tools. Chatter may also be accompanied by a disturbing noise. The ability to accurately predict the onset of chatter or the ability to evaluate its effects would therefore have a large influence on the overall manufacturing system's reliability.

Chatter, a self-induced vibration, is so inconsistent in character that the tendency of a machine to exhibit chatter effect is often not observed at the development stage. Despite much research, the mechanism of chatter is not fully understood. However, there is a consensus that there is a consensus that machine tools chatter only when a simultaneous combination of several cutting conditions occurs. The machine tool, the cutting tool and the workpiece then form a structural system with complicated dynamic characteristics. Consequently, it is difficult to predict the conditions under which chatter will arise or determine the changes necessary to correct the phenomenon. Indeed, in a normal shop floor practice, it is extremely difficult to find any remedy short of reducing metal-removal rates with consequent lowering of the output.

In many past chatter studies, researchers have built models to simulate the behaviour of machine tools. They have then established a general analytical method to treat chatter and have expressed the results in form of charts showing the borderlines of stability. The results have largely not been reliable due to the many simplifying assumptions made. In recent years, acoustic emission has shown promising results of effectively monitoring the cutting process. Acoustic Emission (AE) is a low intensity HF (ultrasonic) signal generated as a result of rapid release of strain energy within a solid material. Measuring from 30 kHz to 30 MHz, these elastic waves propagate throughout the material. They can then be detected by sensors such as piezo- electric transducers mounted on the solid material [1], which in turn convert the energy into electrical signals. The signals are then amplified, filtered, stored, processed and displayed. With computers available for advanced processing and displaying of AE data, the technique can be fully exploited.

The advantages of AE technique include:

(i) AE signal is simply detected by mounting a piezo-electric tranducer on the tool holder.
(ii) The detection of AE signals does not interfere with the cutting process.
(iii) The frequency range of AE is much higher than that of machine vibrations and environmental noise. Therefore a relatively uncontaminated signal can be easily obtained using high pass filters.

2 THEORY OF CHATTER

2.1 Fundamental causes of chatter

Topias and Fishwick [5] viewed changes in cutting conditions as the cause of chatter and specifically pointed out chip thickness variation, work velocity, changes in cutting force behaviour and tool penetration effects as possible chatter generation mechanisms. Kato and Marui [6] considered the phase lag of undulations in successive cutting as the chatter exhibiting force. Small undulations initially produced on a work surface by transient vibration of the workpiece become larger and extend over the whole work surface because a given amount of energy is available for maintaining the vibration owing to the phase lag of successive undulations. The magnitude of this lag is greatly changed by various cutting conditions. Regenerative chatter is a term which defines vibrations which occur in such cutting conditions where the vibratory motion of the system is subject to the effect of undulatory surface produced during the preceding revolution. A great deal of chatter research has concentrated on this regenerative aspect of the process.

2.2 Dynamics of metal cutting

Under chatter conditions a dynamic thrust dF is superimposed on the steady state cutting force. Fig. 1 shows the path taken by a tool vibrating sinusoidally while Fig. 2 shows a situation in which the thickness of cut varies sinusoidally. The former condition is known as 'wave generating' with the latter being referred to as 'wave removing'. In wave generating, it can be seen that the thickness of cut ($\dot{t}_1$), the rate of change of thickness of cut (), the working normal rake angle (γ_{ne}), and the working normal clearance angle (α_{ne}) are continuously varying. The oscillating component F (expressed as $F = F_x + dF_x$) of the resultant tool force normal to the mean cutting direction depends on these parameters.

In wave removing, the rake and clearance angles are constant but the thickness of cut varies. The thickness of cut is measured at the free end of the shear plane, whereas the tool displacements are measured at the tool cutting edge. This means that fluctuations in tool forces (measured at the tool cutting edge) lead the fluctuations in the thickness of cut by an amount equal to the horizontal projection of the shear plane. It can be seen that the component of the resultant tool force will be proportional to the thickness of cut. The force will also change with the work-surface slope, δ_c .

In order to study the practical regenerative-chatter phenomenon, it is necessary to consider the combined effects of wave generating and wave removing. It is obvious that the dependency of the oscillating component of the resultant tool force normal to the mean cutting direction on such parameters as t_1, , γ_{ne}, α_{ne} and δ_c, is complex. If it is possible to obtain an expression for the oscillating component F of the resultant tool force normal to the mean cutting direction, this expression could be inserted in the equation of motion;

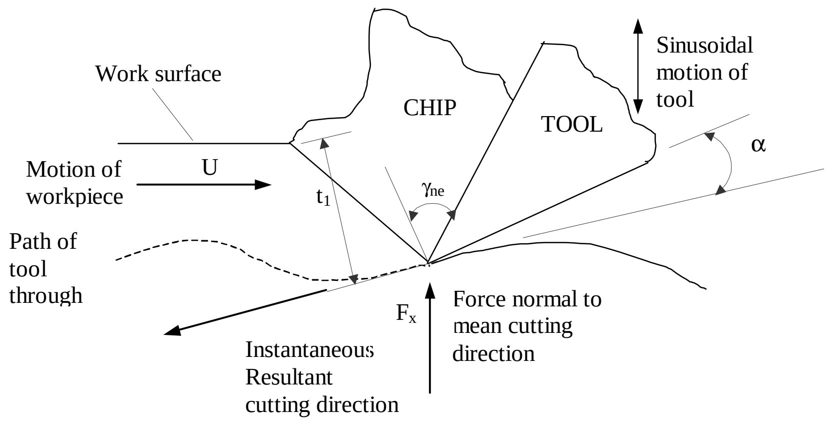


Fig. 1: Wave generating

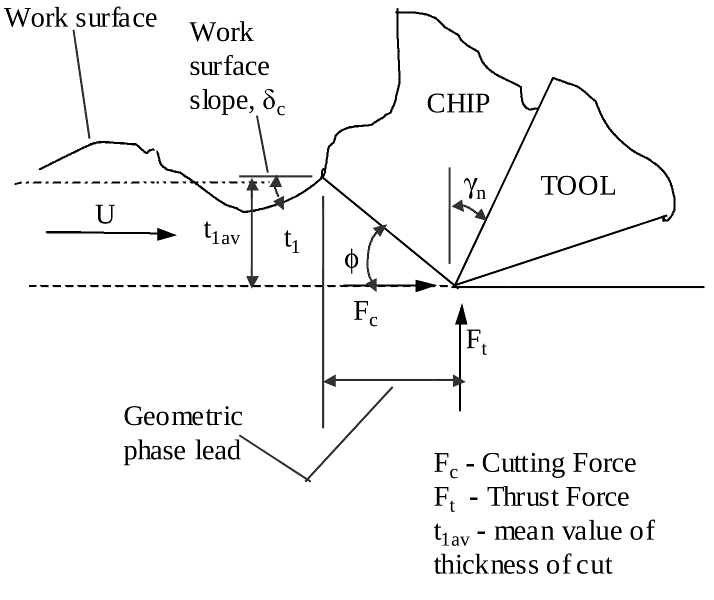


Fig. 2: Wave removing (t_{1av} = mean value of the underformed chip thickness)

$$M_{\varepsilon}\,\ddot{x} + C_d\,\dot{x} + S_{\varepsilon}\,x = F \qquad (1)$$

where,

C_d = Damping coefficient
$M\varepsilon$ = Equivalent mass of a system
$S\varepsilon$ = Equivalent spring constant
x = Displacement
$\dot{x}$ = First derivative of x with respect to time
$\ddot{x}$ = Second derivative of x with respect to time

The resultant expression could then be used to study the stability of the system. Cutting conditions for which the overall damping obtained is negative would be unstable and would cause chatter. Much effort has been made to determine the effects of t_1, $\dot{t}_1$, γ_{ne}, α_{ne} and δ_c on the cutting forces when these parameters are varying cyclically [8]. The complexity of machine tools and chatter mechanism has been the major drawback. Machine tool structures offer unusual complexity due to asymmetry, reinforcing ribs, cut-outs and also the ill-defined boundary between components. The lathe machine, in particular is non-linear in its response, and so is the cutting process [9]. The fact that chatter arises suddenly at critical conditions is a typical behaviour of non-linear systems. Non-linear systems can exhibit very complicated characteristics and their interpretation for model verification or process control becomes difficult.

2.3 Some models used to study chatter

The conventional vibration analysis of a mechanical system proceeds by lumping masses at points and connecting these points with elastic and dissipative elements. After choosing reference systems and sign conventions, the differential equations of motion are derived and solved under prescribed boundary conditions. For the lathe machine, a single degree of freedom system has mainly been used due to its simplicity [2]. In a very elementary analysis, the system is assumed to be linear. The amplitude of the self-induced vibrations is predicted to increase indefinitely once the turning process becomes unstable. This is not so in practice. The amplitude, after a rapid initial increase, stabilises itself at a finite level. A non-linear multi-degree of freedom chatter theory would yield more reliable data. However, very complex theoretical and experimental techniques would have to be employed.

The transfer function theory looks particularly effective in the analysis of chatter. It regards the machine tool and the cutting process as two distinct elements that form a closed loop. An additional feedback path accounts for the chatter effect. A closed-loop model of the metal- cutting system as discussed by Merrit [1] is shown in Fig. 3. An analysis of the stability of this model results in an ingenious and convenient way to determine the onset of chatter. The

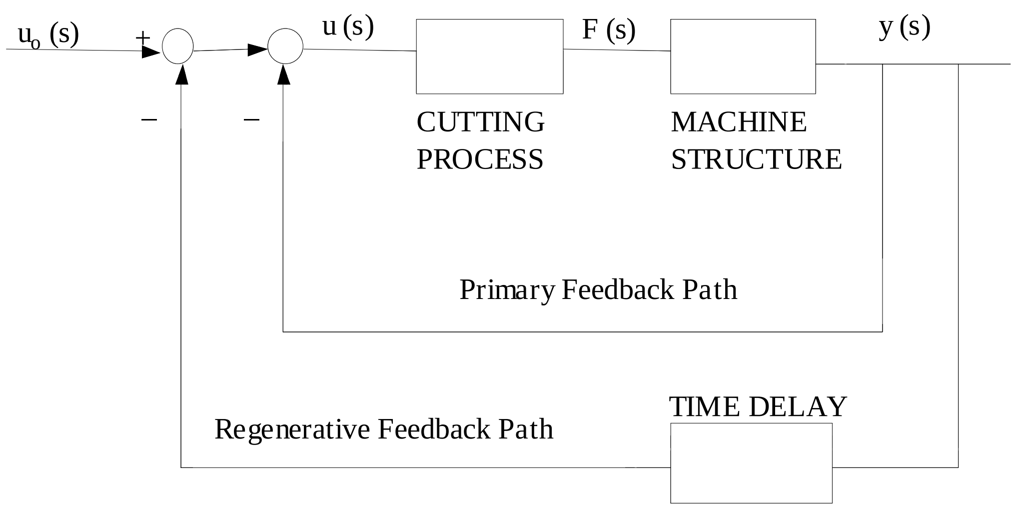


Fig. 3: A closed-loop model of the metal cutting process

fundamental error by most researchers in closed-loop theory is the assumption that steady state cutting occurs. Furthermore the analysis is dependent upon the direction to the cutting orientation.

The existence of unique relationships between the cutting force and tool displacements has also been used to predict the onset of self-excited chatter. Scrinivasan and Nachtigal [10] have described the application of a sequential equation error minimization technique to determine empirically the optimum parameter values in a predetermined set of force component models from dynamic cutting data. The method as described in their paper can only be an off-line identification technique because of the difficulties of measuring relative displacements in actual production and the undesirability of applying an impulsive input to the workpiece during machining.

3 ACOUSTIC EMISSION AND METAL CUTTING

3.1 The metal cutting process

Investigation of the metal cutting processes have often been limited to the more simplified two-dimensional case called orthogonal cutting in which material is removed by a single edge cutting tool which is parallel to the workpiece surface and perpendicular to the cutting direction. A side view of the orthogonal cutting configuration and the nomenclature usually associated with the process is shown in Fig. 4 [11]. As the edge of the tool contacts and presses against the workpiece, material ahead of the tool is sheared and the chip so formed then moves along the tool face. As the chip moves along the tool face, it is deformed a portion of the way i.e. sticking zone; and slides the rest of the way until it looses contact with the tool face. The chip-tool interface, where partial sliding and deformation takes place, is normally referred to as the secondary deformation zone. The newly formed workpiece surface, which results from a separation of the chip from the parent material then moves off on the flank side of the tool.

Three distinct sources of AE can be identified in metal cutting and these are;

a) the primary deformation zone (shear zone)
b) the secondary deformation zone (tool-chip interface)
c) the tertiary deformation zone (tool flank-workpiece interface)

In addition there is a fourth source of AE during metal cutting, which is associated with the fracture of chips and their impact on the tool or workpiece.

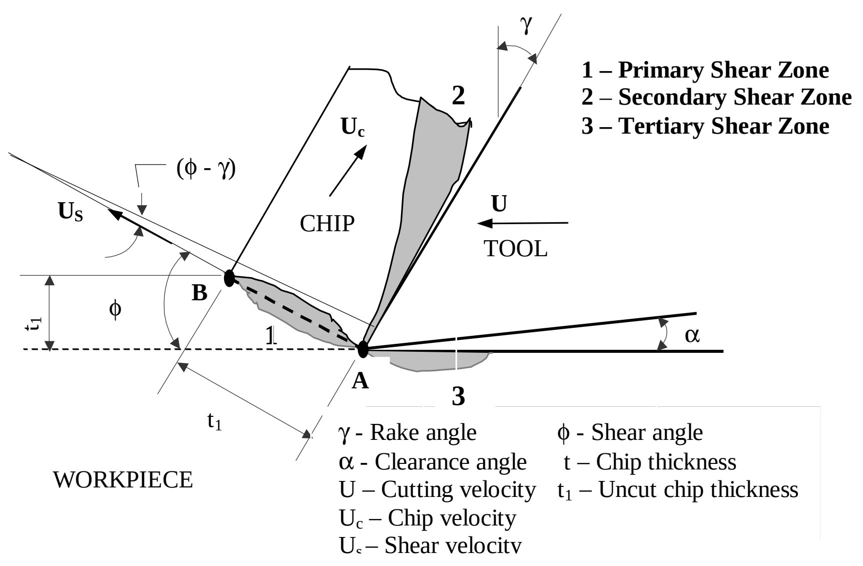


Fig. 4: Nomenclature and AE zones of interest in the metal cutting process

3.2 Theoretical relationships between acoustic emission and metal cutting parameters

Application of AE technique in metal cutting is relatively new. However, the dependency of the signal parameters on the cutting conditions has been ascertained [11, 12, 13]. The signal parameters investigated are the AE RMS value, the number of times the signal level overcomes a set threshold value as well as the count rates. On the other hand, the cutting process parameters investigated include the cutting speed, the feed rate, the varying chip thickness, the rake angle, the number of cutting edges engaged as well as the lubricant used. The AE technique has already shown promising results in the monitoring of tool wear and tool chipping [13, 14].

If a material is subjected to a constant stress (σ) and strain rate ($\dot{\varepsilon}$) the work rate ($\dot{W}$) is given by;

$$\dot{W} = \sigma' \dot{\varepsilon} V \tag{2}$$

where V is the volume undergoing deformation.

Eqn. (2) can then express the rate of plastic work of deformation, which is a source of AE in metal cutting. The energy rate of an emission signal is therefore dependent on the rate of deformation, the applied stress, and the volume of material undergoing process.

On the other hand, the energy rate ($\dot{E}$) of a signal is given as [15]:

$$\dot{E} \,\alpha\, (RMS_V)^2 \tag{3}$$

where RMS_V = RMS voltage.

Assuming the proportions of the plastic work of deformation that go into producing acoustic emission and into generating more dislocations are always in the same proportion, then the emission signal and its source can be directly related using Eqns. (2) and (3). This results in the equation;

$$RMS_V^{\ 2} = C_1 \left(\sigma' \dot{\varepsilon} V \right) \tag{4}$$

where C_1 is a constant of proportionality.

Kannatey-Asibu and Dornfeld [11] extended this relationship to cover the cutting parameters, which essentially are the variables to be monitored using acoustic emission. Their derivation is based on the Ernst and Merchant model, whose configuration is similar to Fig. 5. Apart from assuming the validity of the Ernst and Merchant model, Kannatey-Asibu and Dornfeld assumed the effect of AE from breaking of chips and their impact on the workpiece or tool, on the basis that the chips can be controlled and directed away from the cutting area. Also, using a sharp tool and limiting the test to the initial stages of cutting minimises possible AE generation from the tertiary zone, limiting the sources to only the primary and secondary zones. The following relationship between the emission signal and its source was obtained.

$$RMS_V = C_2 \left\{ \tau_k\, t'\, U \left(\frac{\cos\gamma}{\sin\phi\ \cos(\phi-\gamma)} f \ + \ \frac{1}{3} \left(l + 2\, l_1 \right) \frac{\sin\phi}{\cos\left(\varphi - \gamma \right)} \right) \right\}^{\frac{1}{2}} \tag{5}$$

where,

τ_k = shear strength of the material

t' =width of cut

U = cutting velocity

γ = rake angle

ϕ = shear angle

l = chip- tool contact length

f = feed rate

l_1= length of the sticking zone of the chip- tool face interface

C_1, C_2 = constant of proportionality.

The AE total count, which is the number of times the signal overcomes a threshold voltage, has been correlated in a simple manner to the energy of the signals reaching the transducer [15] (and hence the energy of the signals generated by the AE source). Table 1 shows a summary of the findings. The relationships are derived for the case of continuous type AE signals typically generated by plastic deformation developed during metal cutting.

Table 1: Correlation between AE count parameters and signal energy and power.

AE Parameter	AE Energy; E_{EA}	AE Power; $\dot{E}_{EA}$
RMS Voltage, RMS_V	$\Delta E_{EA} \,\alpha\, RMS_V^{\ 2}\, \Delta T$	$\dot{E}_{EA} \,\alpha\, RMS_V^{\ 2}$
Total Count, N	$N \,\alpha\, \ln E_{EA}$	-
Count Rate, $\dot{N}$	$\dot{N} = \upsilon' e^{-V_s^{1}/A_2 E_{EA}^{A_1}}$	$\dot{E}_{EA} \,\alpha\, RMS_V^{\ 2} \,\alpha\, \dot{N}$

where,

A_1, A_2 = constants

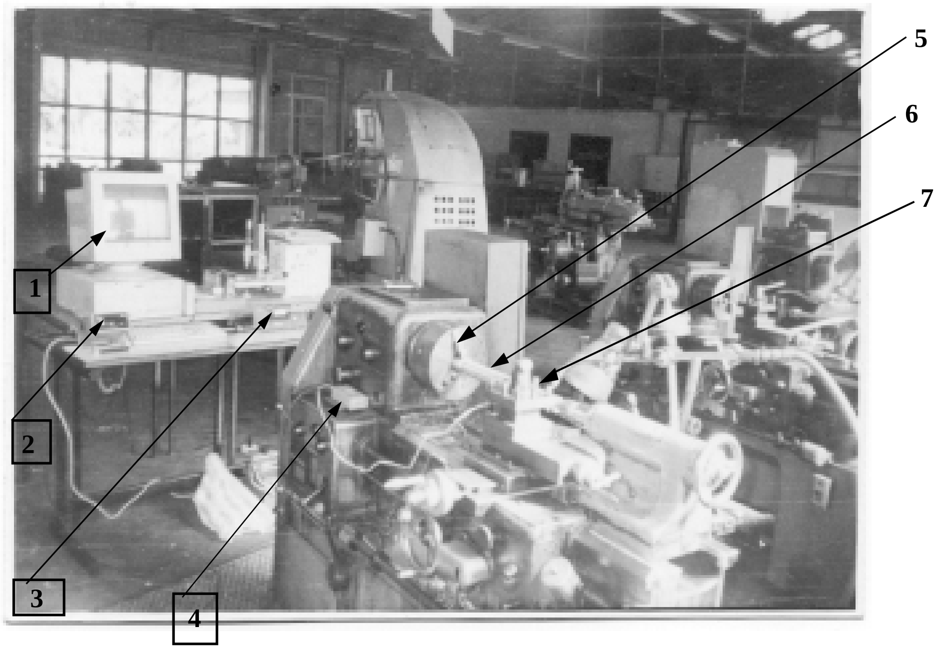
ΔT = change in time

V_s = threshold voltage

N = number of AE counts

υ' = Apparent linear frequency

The models discussed above have not been very successful in predicting AE characteristics during normal machining due to secondary effects, such as chip-tool contact friction and chip fracture during deformation. Further, in normal machining there is always a finite flank wear and therefore AE generated in the tertiary zone should



1-Computer **2**-Main Amplifier **3**-SURFTEST 201
4-Pre-amplifier **5**-Chuck **6**-Workpiece
7-Tool Post

Fig. 5: A photograph of the experimental set-up

not be ignored. In [15], the model represented by Eqn. (5) has been improved by adding the terms τk,U, and l_b (where l_b is the average length of tool flank-workpiece interface) to account for flank wear - land generated AE. As the tool wears, i.e., increase in l_b, the amplitude of AE energy generated at the tool flank-workpiece interface increases. In addition the coefficient 0.5 has been allowed to vary in consistent with results obtained by Liu and Dornfeld [16]. The value of the coefficient depends on the material of the tool and the workpiece, as well as the cutting conditions. Eqn. (5) was, thus, re-written as;

(6)

where,

l_b = Length of tool flank-workpiece interface
C_3 = constant of proportionality
C_4 = factor of signal attenuation between shear zone and the transducer
C_5 = factor of signal attenuation between chip-tool interface and the transducer
C_6 = factor of signal attenuation between wear zone and the transducer
m = material dependent coefficient

$$RMS_V = C_3 \left\{ \tau_k t' U \left[C_4 \frac{\cos\gamma}{\sin\phi \cos(\phi-\gamma)} f + \frac{1}{3} C_5 \left(l + 2 l_1 \right) \frac{\sin\phi}{\cos(\phi-\gamma)} + C_6 l_b \right] \right\}^m$$

6

4 EXPERIMENTAL SET-UP AND PROCEDURES

Fig. 5 shows the experimental set-up. The turning tests were carried out on a turret lathe of 380 mm swing. The workpieces were chuck-mounted and supported by a running centre. The cutting force was monitored by strain gauges attached to the tool holder and calibrated in situ. The AE signals were sampled and processed by the AE instrument system. Fig. 6 shows the schematic diagram of the AE instrument system. The AE instrument system consisted of an AE piezo-electric transducer (PAC m100D, resonant frequency 1 MHz), a pre-amplifier (PAC 1220 A, gain 40 or 60 dB) with a high pass filter (100 kHz), a main amplifier (PAC AE 1A, gain from 0 to 40 dB), a high-speed A/D converter and a personal computer. The high-speed A/D converter sampled at 6.25 MHz with 8 bits resolution between -2.5V and 2.5V and 256 Kbytes sampling numbers. The sampled data was saved in the hard disk drive of the personal computer. After sampling, the machining was interrupted so as to measure tool wear and/or surface roughness. Signal analysis was carried off-line after downloading the sampled data from the hard disk by using floppy diskettes.

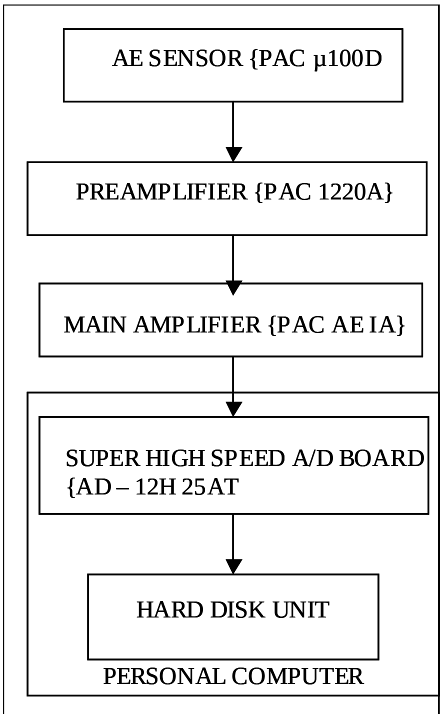


Fig. 6: Schematic of AE instrument system

Flank wear was measured by the Vicker's hardness tester fitted with an optical microscope and a micrometer. The detector unit of the instrument consists of a diamond stylus, which traverses a standard length depending on the level of roughness. The instrument is capable of giving several roughness parameters in a printout. SURFTEST 201 was also used to measure crater wear. The maximum depth of the crater was taken as the amount of wear.
Cutting tool inserts made from tungsten carbide material U505 with AL_2O_3 coating were used in all the experiments. Cutting tips of radii 0.8 mm and 1.2 mm were used. The tool overhang was limited to 20 mm. The total length of the tool holder was 120 mm. The workpieces used in the experiments were bright drawn mild steel, medium carbon steel and stainless steel. The initial diameter of the workpieces was 50 mm while the effective length was 350 mm.

The first set of experiments consisted of varying the depth of cut, the cutting speed, the feed rate and the nose radius. During these experiments, it was necessary to control tool wear because it has an influence on the surface roughness and the onset of chatter. In the second set of experiments, the above parameters were kept constant and turning was continued until tool wear was high enough to cause chatter. As the wear progresses, the general cutting geometry changes considerably especially after the onset of chatter. In this research, crater wear was accurately determined as a measure of the change of tool geometry. Crater wear has a large influence on the effective rake angle.

5 RESULTS AND DISCUSSION

5.1 Effect of cutting conditions on acoustic emission

The following results were obtained from a series of preliminary tests prior to the proper turning tests:

i) There is very little decrease of the amplitude of the sensed signals with increase in the distance from the cutting edge along the shank of the tool holder. For this reason the sensor was mounted at a considerable distance (100 mm) from the cutting edge, so that the chips produced during turning could not easily entangle and pluck off the sensor.

ii) High frequency components were observed not to correlate well with the intensity of cutting conditions. The frequency spectra were calculated by Fast Fourier Transform (FFT) algorithm, which is often used in AE signal processing. It appears logical to conclude that plastic deformation processes generate low frequency signals typically 100-500 kHz. Typical frequency spectra of AE signals obtained during the turning operation are presented in Fig. 7.

iii) High power components existed between 100 and 500 kHz. Therefore, an analysis done in this band would remove or minimize the effects of insensitivity of AE parameters on cutting conditions. The maximum sensitivity of the sensor used was at 350 kHz as stipulated by the manufactures.

iv) The value of the intensity of the frequency spectrum at 0 kHz indicates the reference level and is not related to the measurement [12]. The low frequency components from 50 kHz to 100 kHz were relatively large, even though a high pass filter was used. This indicates that the inherent noise of the filter was significant.

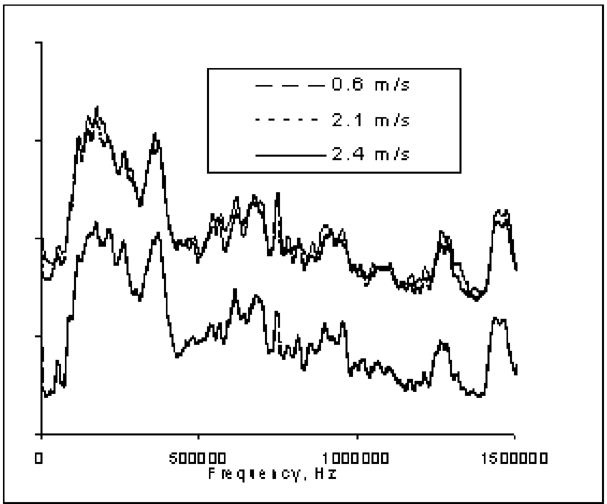


Fig. 7: Typical frequency spectra of AE signals

In the past, researchers have used AE RMS value as a measure of the energy of the generated signals. The square of the RMS value is directly proportional to the energy released during an AE event (Table 1). Results [11, 15] indicate that the AE energy is little affected by changes on feed rate and depth of cut (and hence volume of plastic deformation), contrary to the prediction of the theoretical models. The power spectrums of AE signals obtained in this research generally confirmed this observation. However, the results were found to change considerably with cutting conditions used.

In this research, AE mean intensity level ($\overline{AE}$) was used instead of the traditional AE RMS value. $\overline{AE}$ was found to increase with the depth of cut (Fig. 8), cutting speed (Fig. 9), feed rate (Fig. 10) and flank wear (Fig. 11) for the range of cutting conditions under which there was no chatter. Since the generation of AE signals is intimately linked to the process of chip formation, similar pattern of variation can be expected in AE signals when the basic cutting parameters change. Though the influence of cutting speed on $\overline{AE}$ was still higher, the variation of $\overline{AE}$ with feed rate and depth of cut was far much pronounced than the reported variation of AE RMS value. In this research, $\overline{AE}$ for the frequency range 100 – 500 kHz was calculated using 264 evenly distributed data points.

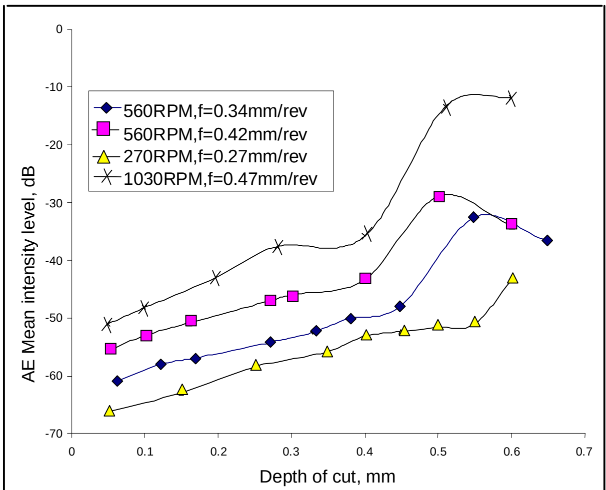


Fig. 8: Variation of AE mean intensity level with depth of cut.

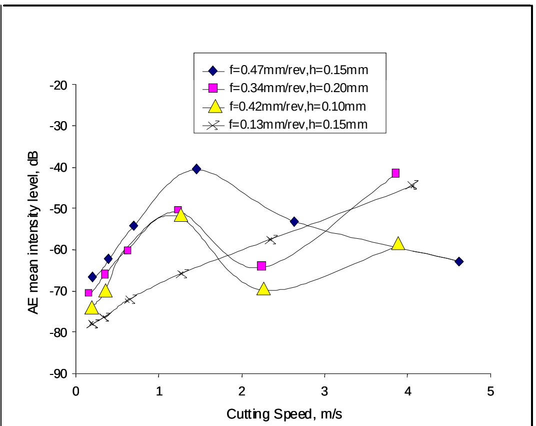


Fig. 9: Variation of AE mean intensity level with cutting speed (Nose Radius = 0.80mm).

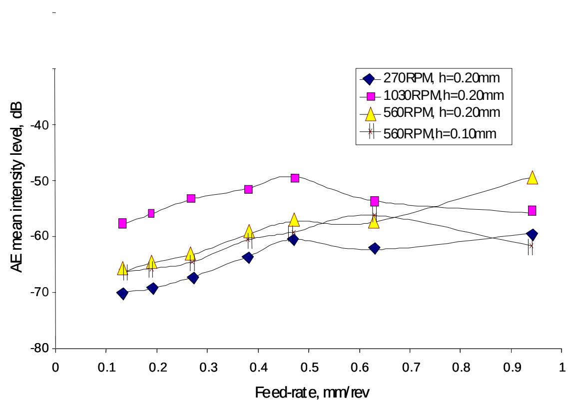


Fig. 10: Variation of AE mean intensity level with feed-rate.

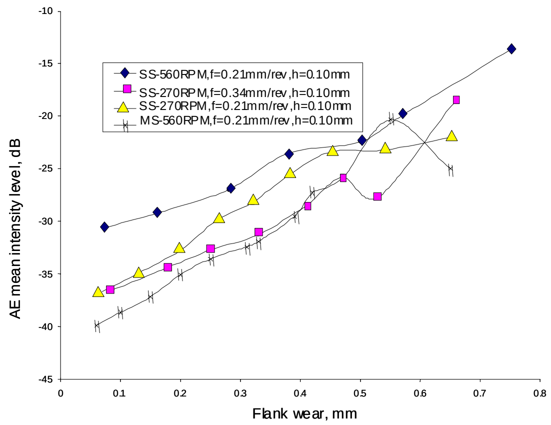


Fig.11: Variation of AE mean intensity level with flank wear.

When the conditions were adverse, chatter was observed and the increasing pattern of $\overline{AE}$ was lost. An observation of the development of crater wear (Fig. 12) indicates that the wear is initially insignificant but accelerates very fast after the onset of chatter. As crater wear grows it tends to eventually intersect the flank wear land. Thus, as the crater wear progresses, the general tool geometry can vary considerably. In particular the effective rake angle increases [17]. As the rake angle increases the amount of AE generated in the cutting zone is expected to decrease, in agreement with the theoretical model (Eqn. 6). The decrease of AE due to an increase in rake angle has actually been observed by Teti and Dornfeld [15]. Weller et al [17] also observed a reduction in sound level due to cratering. Therefore during chatter, AE generated can be reduced considerably.

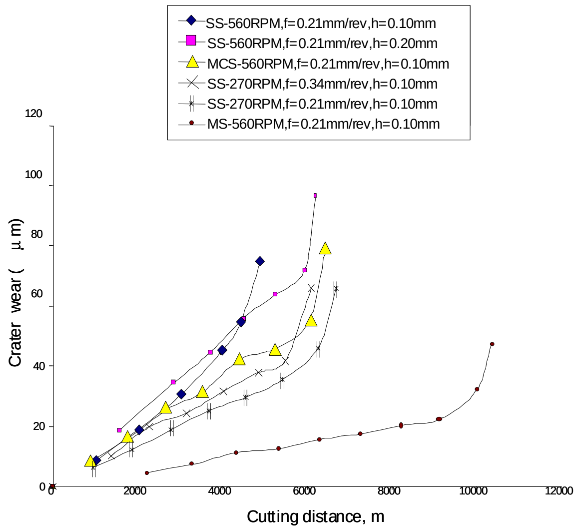


Fig. 12: Development of crater wear with total cutting distance.

However it is important to note that chatter will not always result in a reduction of AE activity by increasing crater wear. Under chatter conditions, the actual depth of cut varies. The amount of AE generated is expected to vary in a similar manner. A major increase in AE activity would be caused when the tool disengages the workpiece and causes impact on the cutting edge, which may result in tool chipping. The effect of chatter on the chip – tool face contact length has not been investigated. However, it appears complex.

The skew and the kurtosis of the power spectrum were also investigated. The skew measures the symmetry of the function about its mean level while the kurtosis is a measure of the sharpness of the peaks. In this research the skew and the kurtosis did not show any specific trend with increasing depths of cut, feed rate or cutting speed. However when these parameters were kept constant, the skew showed an increasing tendency with flank wear (Fig. 13) while the kurtosis decreased slightly (Fig. 14). The patterns were however lost after the onset of chatter. It is hence recommended that higher statistical moments of the power spectrum should be investigated as additional indicators of the tool condition.

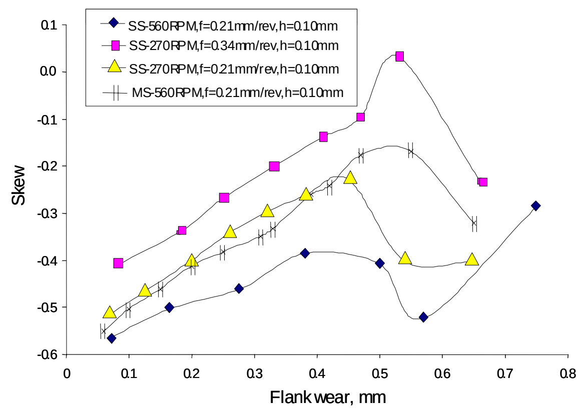


Fig.13: Variation of skew of AE power spectrum with flank wear.

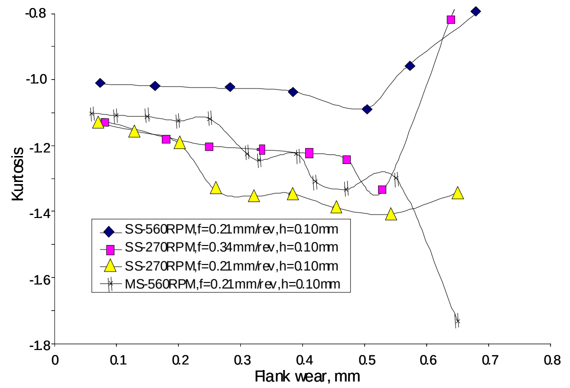


Fig.14: Variation of Kurtosis of AE power spectrum with flank wear.

An increase in the nose radius improved the surface finish as expected from theory. The surface roughness parameters, R_a , the arithmetic mean roughness value and R_{max} , the maximum peak to valley roughness value are given by [18];

$$R_a = \frac{f^2}{31.3\, r_\varepsilon} \tag{7}$$

$$R_{\max} = \frac{f^2}{8 r_\varepsilon} \tag{8}$$

where,

f = feed rate
r_ε = nose radius

It was further observed that an increase in nose radius significantly delayed the onset of chatter. In fact seasoned machinists dull the cutting edge, instead of reducing the speed as a means of eliminating chatter. Flank wear followed a similar pattern as crater wear for all cutting conditions. However, flank wear was comparatively more significant before the onset of chatter.

It was interesting to note that the variation of $\overline{AE}$ with flank wear followed a similar pattern as the development of flank wear with cutting distance. This confirms that Acoustic Emission technique can be used to monitor tool wear. This has been the subject of many researches in the recent past [13, 14, 19, 20]. When the depth of cut, the feed rate and the cutting speed were kept constant, both the cutting force and the surface roughness were observed to increase with flank wear as expected from theory. The relationship that was observed in this research was linear. More so, the linearity was approximately maintained even after the onset of chatter. The possibility of monitoring the cutting force, tool wear and surface roughness using the same technique, even under chatter conditions, has therefore been established.

The count rate is correlatable to the AE signal power as shown in Table 1. It is therefore expected to have a similar trend as AE RMS (or $\overline{AE}$) value as the cutting conditions change. Experimental work in this research confirmed this fact for increasing depths of cut and feed rates at a threshold voltage of 0.25V. The increment in count rates was appreciable as compared to the reported increase in RMS values. As expected, the pattern was lost after the onset of chatter. The count rate showed a peculiar relationship with increasing cutting speed (Fig. 15). An initial decrease of count rate was observed before the increase predicted by Eqn. (5). This increasing tendency was lost almost immediately. The loss was attributed to chatter while the initial decrease could be attributed to the formation of built-up edge. The continuous formation and breaking up of the B.u.e produces a number of acoustic emissions [13] that are added to those generated by plastic deformation. However, throughout the whole speed range, the count rates increase with the nose radius as expected.

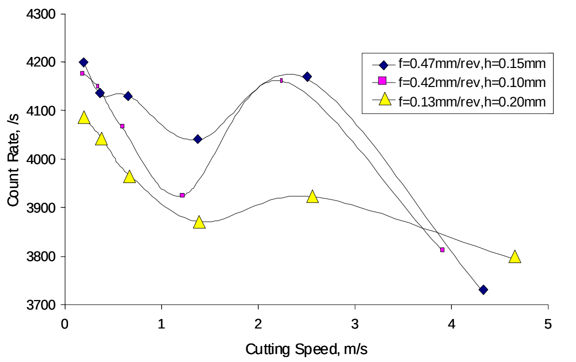


Fig. 15: Variation of count rate with cutting speed(Nose Radius = 0.80mm).

The variation of count rate with flank wear (threshold voltage = 1.50V) is shown in Fig. 16. Despite the general increase in count rate with flank wear, it cannot be concluded it is a good parameter to monitor tool wear and subsequent chatter. The count rate values showed a substantial scatter and the increasing patterns were not similar. However this does not rule out the use of count rate. One parameter that can substantially change the results is the threshold voltage chosen.

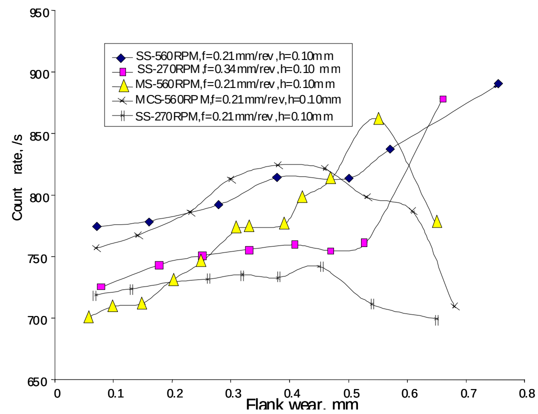


Fig. 16: Variation of count rate with flank wear.

5.2 Stability charts

The cutting speed, the feed rate and the depth of cut are the basic machining conditions, which have been confirmed to influence machine tool chatter. The extent of tool wear and the cutting geometry were also observed to influence chatter. For instance when the nose radius is increased, higher speeds can be reached before the onset of chatter. Other factors, which have been established to influence chatter, include the tool overhang, the size and material of workpiece as well as the material of the cutting tool.

When the system starts to vibrate, often we do not know how to determine which element in the system is least stable. Stability charts would help solve the problem. However, numerous stability charts would be required for a single machine because the cutting conditions can be varied independently. Observed changes in AE signal parameters offer a more convenient and accurate method (compared to analytical methods) of determining the onset of chatter as no modelling assumptions of the system are considered. In this research, it was for instance found that (Fig. 17) for a depth of cut of 0.6 mm, increasing the feed rate from 0.15 mm/ rev (point A) to 0.3 mm/ rev (point B) eliminates chatter when turning stainless sped at 560 rpm. This is contrary to the normal shop floor practice of reducing metal removal rates in order to eliminate chatter. It is further observed that below a feed rate of 0.4 mm/rev, the machine is stable for all cutting speeds and feed rates.

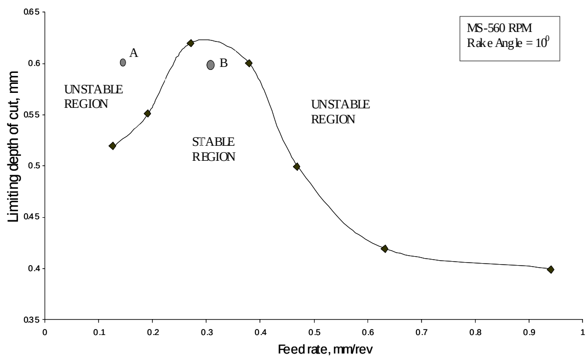


Fig. 17: Stability chart plotted using changes in AE mean intensity level.

6 CONCLUSION

It has been established that the cutting speed, the feed rate, the depth of cut, the amount of the tool wear and the cutting geometry all influence the stability of the cutting process. Further, the changes occurring to AE signal parameters can be used to identify the onset of chatter and hence plot stability charts. Apart from showing the borderlines of stability, such charts help in identifying the changes required to eliminate chatter with minimum or no loss of production.

The sensitivity of AE signal parameters to the cutting conditions was found to be maximum in the frequency range 100-500 kHz. AE mean intensity level and AE count rate (at a properly chosen threshold voltage) increased almost linearly with the cutting speed, cutting depth, feed rate and tool wear up to the onset of chatter when the pattern was lost. During chatter the AE signal parameters fluctuated significantly. Higher statistical moments (skew and kurtosis) of the AE signals were found to be sensitive to tool wear and the subsequent chatter. Frequency techniques yielded better results compared to count techniques for the cutting conditions used in this research. It is generally concluded that AE technique offers a good adaptive method for on-line monitoring of the cutting process since AE signal parameters are sensitive to the cutting conditions.

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