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Review

Prospects for in-process diagnosis of metal cutting by monitoring vibration signals

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Vibration signals from various metal cutting processes in a frequency range of a few Hz to several MHz have been investigated by many researchers for their possible application to an in-process cutting condition monitoring system and some remarkable laboratory results have been reported. In spite of many very interesting demonstrations of feasibility in laboratories, numerous attempts to apply the technology to manufacturing conditions have not been very successful. The main objectives of this brief review are to summarize the key points of various published reports and to discuss the critical technical issues which are hindering transformation of the laboratory results to more broadly applicable technology. The vibration signals from metal cutting processes contain very useful information and offer excellent possibilities for in-process diagnosis of many critical metal cutting problems including tool wear. But the current state of knowledge still consists mainly of empirical observations, many of which need further clarification. Some of these key issues requiring future studies, particularly those issues related to in-process monitoring of tool wear, are discussed in this review.

1. Introduction

The ultimate objective of any machining process is the production of a part of a specific shape with acceptable dimensional accuracy and surface condition from an appropriate workpiece. Deviation of the machining conditions from a prescribed plan may influence the final part quality and must be carefully examined by the machine operator. In addition to the basic responsibilities of operating the machine, i.e. loading and unloading parts and changing tools, a machine operator is also responsible for monitoring various aspects of the cutting process, such as tool wear, tool breakage, chip disposal, cutting temperature, surface finish, machine chatter, and part dimensions. If some or all of these monitoring functions can be carried out automatically, the burden on machine operators and the risk of human error will be reduced. The need for such monitoring systems for efficient machine operation is clear, but progress toward developing and implementing them has been slow.

Among examples of targeted monitoring technology are attempts which have been made to measure part dimensions during the process [1] (e.g. air gauge), and to measure the temperature of the cutting edge during the process (e.g. using a thermocouple embedded in the tool as a means to determine the state of the cutting edge). But systems acceptable in a factory environment and universally applicable to a variety of operations have yet to be developed. Adjustments of machining parameters from preset conditions cause related changes in other system variables, such as forces, temperature, power consumption, and vibration; knowledge of the relationships between these system variables and various cutting parameters would assist and enable selection of an appropriate system variable for in-process monitoring.

It has been shown [2] that some system variables, such as cutting forces, are closely related to changes in cutting parameters; thus, some of these variables can be used to monitor the state of the cutting edge for selected cases. However, a monitoring device for cutting forces that is simple, accurate, and durable enough for a manufacturing environment has not been developed. A major difficulty is the accurate measurement of cutting forces without reliance on a sensor, or sensors, placed close to the cutting edge where the environment is hostile. Several proposed ways to monitor the cutting forces through remotely located sensors are generally complicated by the difficulty of distinguishing the components of force necessary for the movement of the machine from the actual cutting forces [1]; hence, the sensitivity of such a system has generally not been sufficient for monitoring the cutting process in detail.

A limited amount of information can also be obtained through other related system variables [3], such as the power consumption of various drive motors on the machine; however, the sensitivity and reaction times of power monitoring systems are strongly influenced by friction in the machine components and by system inertia. Analysing short-time events with a power device, and hence, monitoring detailed mechanisms of the cutting process, is not yet possible.

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The vibration signatures of machining processes, including both the relatively low-frequency vibrations of tooling systems [4] and the high-frequency acoustic emission (AE) signals from the chip formation process [5], have been investigated as potential sources for an in-process monitoring tool for metal cutting. The acoustic waves travelling through the machine tool carry not only the acoustic emission signals originating from the chip-making process, but also some information about the dynamic responses of the tool holders and other machine parts. Because the AE signals carry a great deal of information about the originating sources and travel rapidly through the machine structure, an appropriate sensor located remotely from the environmentally hostile cutting zone can potentially monitor even the very short events of the cutting process that cannot be monitored by any other means. Therefore, vibration monitoring presents a unique and attractive opportunity for monitoring the details of a cutting process. The great amount of information that vibration carries, however, also poses formidable challenges for researchers to isolate and characterize only those specific signatures relevant for the diagnosis of a particular condition.

This report presents a critical review of studies of AE from metal-cutting processes. The objectives are to identify the essential technical areas requiring further investigation, and to assess the prospect of developing a comprehensive cutting process monitoring system based on vibration signatures. The characteristic responses of individual sensors, the transfer characteristics of the signal transfer medium from various AE sources to sensor or sensors, and the methods of processing signals have very significant effects on observed signals [6]. This report does not, however, discuss the instrumentation aspects of sensing and interpreting vibration signals. The main emphasis of this review is the behaviour of average signals in the time domain of AE signals, in relation to specific physical events of the cutting processes. Some signal frequency characteristics are discussed as necessary for the correct interpretation of the literature. Studies covering primarily the audible frequency range of signals are treated separately from the studies mainly concerned with acoustic emission frequency range. Literature concerned primarily with the vibration of tool and machine components is discussed in the context of low-frequency vibration studies, and high-frequency phenomena are discussed in the context of acoustic emission studies.

2. Vibration monitoring of machining

2.1. Low-frequency vibration

The various components of cutting forces fluctuate rapidly. These fluctuating conditions are reflected in the vibration spectra of the cutting tools and machine components. Most of the energy of the noise associated with this vibration is within the audible range of frequencies [4], and therefore the sound of machine vibration is one of the most sensitive sources of information available to a machine operator for the diagnosis of the operating condition of his machine and the status of the cutting process. A well-trained machinist can detect from the cutting noise the sign of an over-worn cutting edge, and he often can foretell an impending cutting-edge break. Therefore, researchers have questioned whether this vibration noise-based diagnostic ability of human operators can be automated. What specific information is used by the operators for making their decisions? How is the important information extracted from the noise signal?

Weller *et al.* [4] attached an accelerometer (2 to 40 kHz) on the tool post. The cutting noises from machining steels with cemented carbide tools were recorded on a tape recorder. The variations of the signal intensity and its characteristic frequencies as a function of tool wear were analysed. They observed that worn cutting edges produced high-frequency vibration energy that was not observed in the sharp cutting tool noise. They also observed that the higher frequency portion of the monitored signal contained the fundamental frequencies and their harmonics, and that these fundamental modes were above 4 kHz. From these observations, they developed an approach using the ratio between the intensity in the signal band above 4 kHz, which showed a strong dependence on the degree of tool wear, and the intensity in the relatively insensitive signal band below 4 kHz as the indicator of tool wear. This approach, according to Weller *et al.*, minimizes the effect of the sensor sensitivity and the signal amplification factors on the critical intensity of the signal. Selection of the two frequency bands is determined by the fundamental vibration frequency of each tooling system. The primary tonal frequency of the machine tools used by Weller and co-workers was above 4 kHz. In a recent study, Pandit and Kashou [7] also reported that the fundamental frequency of a tool holder similar to one used by Weller *et al.* was about 5 kHz, essentially confirming the earlier observation.

Taglia *et al.* [8] also investigated the mutual relationship between tool wear and vibration power spectrum over a frequency range of 0.5 Hz to 30 kHz. The vibration energy spectra from several series of very carefully controlled machining experiments were recorded through an accelerometer attached to the tool holder. All machining parameters, including diameter, length, and location of each cut, were kept constant throughout each series of experiments to minimize system-related variations. Cutting tools were cemented carbides and workpieces were 0.4% carbon steel. The change of the energy content of the power spectrum in frequency bands of 0 to 1, 0 to 2.5, 0 to 5, 0 to 12.5, 0 to 30 kHz was analysed in relation to the progress of tool wear. According to this study, most of the signal power is contained in frequencies less than 10 kHz, and the total spectra energy is not sensitive to tool wear. Also, no regular correlation between the progress of tool wear and the change of the total spectrum power was observed. However, spectrum power in certain narrow bands showed a strong relationship to tool wear. For example, the energy in the spectrum under 2.5 kHz was only a small fraction of the total energy but it increased strongly with tool wear. One very interesting observation reported by Taglia *et al.* is that the spectrum energy in the narrow frequency band which is sensitive to tool wear started to decrease rapidly as the cutting edge developed excessive wear.

Observation by Taglia *et al.* that the energy spectrum in certain frequency bands is much more sensitive to tool wear than the total energy spectrum is in essential agreement with the report by Weller *et al.* [4], although the most sensitive frequency band in the case of Taglia *et al.* is substantially lower than the cut-off frequency used in the experiments by Weller *et al.* This significant variation of the specific wear-sensitive frequency band from one system to another raises a serious problem for the practical implementation of this observation. It is conceivable that the critical signal band can be identified before every cut, but the progress of the cut through a complex workpiece, or a change of the part on the machine might change the characteristic frequency band.

A somewhat different approach to using vibration signals for monitoring drill wear was developed by Yee and Blomquist [9, 10]. In this system, an accelerometer is mounted on the workpiece and the vibration signal is analysed in the time domain. Successive segments of vibration signal equivalent to one full revolution of the drill bit are analysed for the presence of pulses. If a pulse of amplitude exceeding a preselected level is detected for four cycles (rotations) in succession, the drill bit is considered worn beyond its useful life. The threshold energy level of pulses indicating worn edges can be self-calibrated by the system using the drilling signals from sharp bits as a reference.

The source of pulses used as the key indicator of worn drills in this approach is assumed to be the rubbing interaction of the workpiece and drill shank in the hole. As a drill tip wears, the axial force increases, causing deflection of the drills and rubbing between the side of the drill and the inner wall of the hole. If the diameter of the drill is large, or a very stiff material (e.g. solid carbide) bit, is used, the sensitivity of this detection scheme is expected to decrease. This system has been adopted successfully for drilling operations using relatively small-diameter bits. This drill wear detector was also evaluated for possible application as a wear sensor of end-mills [11], and favourable results were reported.

Approaches using the vibration signals of the system have shown promising results for many different types of cutting operations. If properly applied, vibration signal analysis can detect worn tools for turning, drilling, milling, and broaching. The intensity of the signals for the audio frequency range of interest in this approach generally is high and relatively easy to monitor. In addition, the widely acknowledged shop-floor practice of machine operators using noise to determine the state of cutting makes acceptable the concept of monitoring tool condition through audible frequency-range vibration signals.

The suspected weakness of this approach, however, is that the noise from other moving components of the machine can easily interfere with the vibration signal containing the tool condition information. Also, the system must be tuned for each specific operation, or even each cut, for reliable operation. Because the measured vibration characteristics depend on the machine, the size and shape of the parts, and the types of cuts, in addition to the conditions of the tools, the system is not easily interchangeable. The reported studies on turning were done on manually operated machines only; the effectiveness of these techniques for numerically controlled machine tools, which tend to have heavy turrets and massive tooling systems, needs further investigation.

Depending on the types of cutting processes and the specific functions required by a given application, an audio frequency approach can provide a useful solution. However, there are still many more problems to be resolved before a widely acceptable tool condition monitoring system based on this technology can be realized. Some of the problems encountered during earlier studies, however, may no longer be basic technical problems. With advanced digital electronics and integrated circuit technology, in-process determination of the fundamental frequency for every case, and calibration of the individual systems in real time are technically and economically feasible, as long as the basic conditions necessary for the signal calibration can be specified. If the fundamental knowledge of the relationship between tool wear and tool vibration is improved and the relationship can be defined in terms of physically definable parameters, the development of a reliable tool monitoring system based on low-frequency system vibration signals should be possible. Any significant improvement of tool wear monitoring technology in the future, therefore, will require progress toward understanding the nature of the relationship between tool wear and vibration.

2.2. Acoustic emission

2.2.1. Overview

The physical process of removing metal chips from a large workpiece with a sharp cutting edge requires severe plastic deformation of the metal at a very high strain rate. In most cases a fracture process also plays a significant role. All of these processes are well-known sources of AE [12], and monitoring the AE signal from the cutting zone can provide very useful information concerning the status of cutting edges as well as the process itself. Because the frequency range of the AE signals can be very wide, high-frequency AE sensors combined with suitable high-pass filters can provide signals that are immune to the lower frequency system vibration noise.

In recent years many researchers have investigated AE signals from metal cutting processes, and the feasibility of their application for in-process monitoring of tool conditions has been explored. Details of the published results from many of these investigations are summarized in several recent reviews [13–15]. In this report, only those earlier papers critical for assessing the future needs of research on this subject, and some of the inconsistencies among the results reported by various research groups, will be briefly discussed.

Some key approaches by most of the investigators are essentially the same. For example, most of the published studies concentrated primarily on the lathe turning of metals, and only a few studies extended this technique to different types of operations [16] or materials [17, 18]. The approaches used for the analysis of the signals were also very similar, generally relying on the time domain variation of the AE signals within a selected frequency band. One important general contribution by these earlier investigators confirms that all physical actions involved in the chip-making process are sufficiently active acoustic events that the AE signals from the cutting process can carry detailed information about the tool, chip, and workpiece interactions.

The deformation processes of the metal-cutting and chip-formation mechanism provide a multitude of potential AE sources. Some of these AE sources, such as dislocation activities, are frequent but generally low-energy events, while others, such as breaking of hard inclusions or microchipping of the tool material, can be less frequent but very high-energy events [12]. Consequently, the composite AE signals from most of the metal-cutting processes appear as a continuous wave of very high-frequency content, resulting from densely packed AE events, with occasional pulse events (bursts) of higher energy [19]. The factors which have the most influence on the energy level of the AE signals are the strain rate of shear deformations, the yield strength of the workpieces, and the volume of the deformation zone [20].

2.2.2. *An empirical model*

A quantitative model of AE for orthogonal machining with continuous chips has been proposed by Kannatey-Asibu and Dornfeld [21]. For this simple case, the cutting energy is consumed mostly as the plastic deformation work necessary to generate chips. Therefore, these authors proposed that the dominant mechanism of AE source for this case should be mostly dislocation-related processes and the energy of the signal should be related to the rate of plastic deformation work. Furthermore, the authors assumed as a reasonable starting point of model development that a constant fraction of the work of plastic deformation will be converted to AE energy. Under these conditions, the square of RMS average of AE signal intensity should be proportional to the rate of plastic deformation work, and the magnitude of the rate of plastic deformation work can be estimated by using established models [22] of metal cutting, if some key conditions can be defined.

To prove the validity of this approach, they developed an equation to estimate the work of plastic deformation from the mechanical properties of the material and the geometric parameters of cutting. The calculation assumed that only continuous chips are formed, predominantly by a plastic shearing process, and very little fracturing occurs. It was also assumed that the shear stress and the thickness of the shear zone remain constant during the cut. Although this last assumption generally is not true, these authors cited a reference [23] supporting the view that the thickness of shear zone would remain fairly constant under the cutting conditions used in their study. For the estimation of deformation along the rake face of the tool, the authors assumed the length of the sticking zone to be about one-half of the measured contact length. Because this analysis considered only sharp cutting edges, plastic deformation at the contact area between the tool flank and the workpiece was ignored. From their analysis, the following expression for the rate of plastic deformation work was obtained.

$$\text{Rate of plastic work} = C\left[\tau B u\left(\frac{\cos\alpha}{(\sin\phi\cos(\phi-\alpha))}\right)t + 1/3(l+2l_1)\frac{\sin\phi}{\cos(\phi-\alpha)}\right] \quad (1)$$

where the first term in the brackets represents the plastic deformation work done at the primary shear zone while the second term is from the plastic work done at the secondary shear zone along the rake face. The symbols, τ, B, u, and t are the shear strength of the workpiece, width of cut, cutting speed, and feed rate, respectively. l and l_1 are the chip-tool contact length and the length of the sticking zone in the contact, α and ϕ are the rake angle of the tool and the shear angle of the cut. The proportionality constant, C, represents the fraction of the total plastic deformation energy converted to acoustic energy.

A series of cutting tests was performed at four different cutting speeds and four different rake angles using 6061-T6 aluminium and SAE 1018 steel as workpieces. Comparison of measured RMS value of the AE signal from these tests and the corresponding estimates of plastic deformation work rate from the use of the model (Equation 1) indicated that the measured RMS AE increased continuously with increasing rake angle, while corresponding estimates of plastic work rate decreased steadily. Furthermore, the magnitude of the difference increased as sin α, where α is the rake angle. From this observation and using the proportionality of the square of RMS AE and the plastic deformation work rate, the authors obtained the following expression as an AE model for orthogonal machining of continuous chips.

$$\text{RMS AE} = C_1\sin\alpha\left[\tau B u\left(\frac{\cos\alpha}{(\sin\phi\cos(\phi-\alpha))}\right)t + 1/3(l+2l_1)\frac{\sin\phi}{\cos(\phi-\alpha)}\right]^{1/2} \quad (2)$$

C_1 is a modified proportionality constant. The authors reported that the agreement between the estimated values of RMS signal intensities using this modified model and the experimentally measured values was reasonably close.

The most important point revealed by this study is that the portion of cutting energy dissipated as AE is strongly dependent on the rake angle used and that the change of average intensity of AE as function of rake angle is opposite to the resulting change of the necessary energy. One key weakness of the model, however, is in the proportionality constant, C_1, which has been normalized based on the limited amount of experimental results gathered from the study. For example, the test did not include negative rake angles, which are more often used in industry. The validity of extrapolating this result to negative values of rake angle needs further examination.

The detailed mechanisms of the chip formation process vary a great deal and depend upon many different conditions, such as the physical and mechanical properties of workpieces and various independent machining parameters. Far more understanding of the AE source mechanisms is needed before the true nature of this relationship can be established. Moriwaki [24] pointed out that the type of cutting tool material used can also change the average amplitude of a continuous AE signal. According to Moriwaki's experiment, the AE amplitude was lowest with carbide cutting tools; cubic boron nitride and ceramic tools generated higher amplitude AE. The loudest tools were the cermet tools. This effect of tool material on AE amplitude, however, may be due to causes beyond the conditions assumed for the analysis, such as thermal cracking, as discussed later in this report.

2.2.3. RMS AE and tool wear

One very important goal of studying the AE from metal-cutting processes has been understanding the tool-wear-related AE variations and evaluating their possible application to an in-process tool condition monitoring system. Two such possibilities have been identified. According to these investigations, increasing flank wear will increase the level of AE energy (RMS voltage of signal) and increase the density and total number of pulse events (event counts) exceeding a given threshold energy level. Iwata and Moriwaki [5, 25] observed that the RMS voltage of their AE signal increased significantly as the carbide tool wore during the machining of a carbon steel workpiece similar to AISI 1045. They originally reported a result showing that flank wear has a much more significant effect on the average RMS voltage of the signal than the change of cutting speed, over a range from 150 to 250 m min^{-1}. However, a later study on essentially the same application by Miwa *et al.* [26] showed that increasing cutting speed has a major effect in increasing the average AE signal. Miwa's group also reported that the effect of tool wear on the average AE signal is greater for the higher cutting speed than for a low-speed cut, and the flank wear dependence of the average AE signal becomes very pronounced at high cutting speeds. Moriwaki also reported [24] that the magnitude of the average AE signal increases abruptly as the tool wear penetrates through the thickness of coatings on coated cutting tools.

Kannatey-Asibu and Dornfeld [27], and Lan and Dornfeld [28] also studied the relationship of the mean value of the AE signal to the flank wear of tools cutting SAE 4340 steel, and reported mean AE level increases with increasing flank wear. This group also observed that the rate of AE level change decreases or stops when the flank wear reaches some intermediate value. They attributed this phenomenon to the effect of the rapidly developing crater wear at this point of tool life, which tends to reduce the mean AE. According to this group, when both flank and crater wear are present, the skew of the statistical distribution of the RMS value of the AE signal above and below its mean is a better indicator of tool wear than the mean level itself. Another interesting result reported by this group is that the frequency spectrum of the monitored AE signal had dominant frequencies at 80 and 150 kHz, and that the power spectrum amplitude at these frequencies increased with increasing tool wear.

Inasaki and Yonetsu [29] carried out an extensive series of machining tests of medium- (0.45% C) and high- (1.0 to 1.1% C) carbon steels using carbide tools. The AE amplitude, according to this study, is independent of the depth of cut and the feed per revolution but increases continuously with increasing cutting speed. For a constant cutting speed, the AE amplitude increases linearly with increasing flank wear. Test results showed that the amplitude of AE increases approximately linearly with increasing flank wear over the entire range of cutting speed, and these researchers were able to establish a reference chart depicting the relationship between flank wear and AE amplitude for a range of cutting speeds. Using their empirically established reference chart, this group carried out in-process monitoring experiments of tool wear. A series of cutting tests was carried out while the AE amplitude was continuously monitored, and the flank wear was estimated by using the AE amplitude-to-flank wear relationship. Results obtained in this way were compared with values of flank wear measured optically between cuts. In this particular test, the cutting speed, feed, depth of cut, and even the workpiece material, were changed several times. Only the cutting tool remained the same throughout the series of tests. The authors reported that flank wear determined by the AE monitor and the optically measured value showed very good agreement, with less than 15% maximum deviation from the measured value. In contrast, Iwata and Moriwaki reported a much larger degree of scatter than 15% from similar experiments and also increasing scatter in experimental data with increasing cutting speeds.

2.2.4. Pulse AE and tool wear

Tool wear also is reported to have a significant effect on the density of pulse events in the metal-cutting AE signal. Iwata and Moriwaki [25] observed that the number of pulse counts per cut (the pulse density) increased with increasing flank wear up to about 120 μm, but the count rate remained relatively constant for flank wear above 120 μm. They reported that the total counts of the pulse events continuously increased with increasing flank wear. Although the pulse density remained fairly unchanged with flank wear over 120 μm, the data showed a significant degree of scattering, whereas the total counts of pulse events remained much more consistent. Inasaki and Yonetsu [29] observed a sudden increase in the event count rate after a tool developed extensive flank wear, and they reported a considerable increase in the standard deviation of the count rate at this point. The authors attributed this change to the development of microcracks in the tool.

Although the total count of pulse events seems to be well correlated to flank wear, many problems need resolution before this relationship can be used for in-process monitoring. One problem is the requirement that the system be calibrated for each specific case, while the results obtained on one machine often are not applicable to another. A second problem is the arbitrariness of selecting the threshold energy level for the pulse events to be counted. Iwata and Moriwaki [25] showed that the total count against flank wear curves varied rather significantly with a change of cutting speed if a threshold energy of 50 mV was used; but, when 100 mV was used for the threshold energy, five cuts with cutting speed ranging from 150 to 250 m min^{-1} produced a set of total count against flank wear curves virtually overlapping each other. It is apparent from this study that a systematic method of determining the proper pulse energy threshold level must be defined for any extension of the results. Therefore, until the sources of the pulse events are identified and their physical relationship with tool wear is understood, a generally applicable tool wear monitor system based on the pulse monitoring approach will be difficult to develop.

2.2.5. AE from tool fracture

Inasaki and Yonetsu [26] also studied the effect of tool fracture on the AE signal. They reported that, when part of the cutting edge breaks, a sudden increase in the AE amplitude is observed. Analysis of data from a series of cutting tests using various speeds, depths of cut, and feeds also showed that the ratio of the amplitude of AE after edge breakage to the amplitude of AE just prior to the edge breakage at least exceeded 1.8. Using this ratio of 1.8 as the minimum AE amplitude shift criterion for a tool breakage event, this group was able to detect small edge breaks with a fracture surface area of about 0.1 mm^2. However, if the edges wore significantly before the break, the increase of AE amplitude due to the worn edge effectively decreased the shift in AE amplitude caused by the edge fracture. According to this study, the band of the AE signal power spectrum particularly sensitive to flank wear was below 300 kHz, and by using a 300 kHz high-pass filter, they could reduce the effect of tool wear on the AE amplitude. With a 300 kHz high-pass filter in the signal circuit, the monitored AE signal showed a very large burst-type AE from tool fracture. In this case, they were also able to detect AE burst events from microcracking of the tools. If the cutting edge with microcracks was continuously used, the density of pulse events in the AE signal was increased.

The cause of the AE intensity increase with partial breaks of the cutting edge is not explained in the report. Considering that both change of depth of cut and change of feed had no significant effect on the AE amplitude and that the cutting speed did not change upon tool break, the only significant change caused by the edge break would be the cutting edge geometry. Kannatey-Asibu and Dornfeld, as discussed earlier, and Lan and Naerheim reported that increasing tool rake angle will increase the average AE amplitude. If the proposed model by Kannatey-Asibu and Dornfeld is applicable for the negative rake angles, effective reduction of rake angle as a result of partial breakage of the cutting edge should decrease the AE amplitude. This observation again highlights the need to evaluate the proposed AE model for the negative rake angles. Another possible source of increasing noise is the roughness of fractured surface causing more severe rubbing conditions at the chip–tool interface.

Moriwaki [24] also studied the AE from tool breakage. An alloy steel plate was machined on a lathe with ISO grade P20 carbide tools. The interruption of cutting caused by turning the side of the plate on a lathe induced frequent edge breaks. The fracture events of the cutting edges emitted very high-energy pulses. The maximum amplitude of the averaged AE amplitudes showed good correlation with the cross-sectional area of the fractured surface. The author reports that an extrapolation of this relationship to larger areas of fracture surface seems to fit experimental data obtained from transverse rupture tests of the tool material, indicating that the impact speed or the rate of increase of the stress causing the fracture does not have much effect on the AE amplitude within the range of conventional cutting speeds. Following the high-energy AE pulse event originating from the tool breakage, the average AE level showed an abrupt increase. Moriwaki attributed this simply to abnormal cutting conditions resulting from continuous machining with a broken cutting edge. In addition to being a function of the size of fracture, the amplitude of the AE burst signal from tool breakage was also a function of the cutting tool material. Simple tool breakage detection devices based on this technology have been offered commercially, but neither commercial systems nor other monitoring schemes that follow this approach and have been demonstrated successfully in various laboratories have been proven successful in actual manufacturing applications. One key difficulty of relying on some impulse signal of fixed magnitude as discriminator is handling extraneous noise impulses inherent in materials or in the machine tool structure and separating them from real signals.

2.2.6. Other sources of AE

Although detecting tool wear and tool breakage attracted most attention, investigators of the AE from metal-cutting processes also reported many other interesting observations. Kakino *et al.* [30] studied the effect of microcracks on the cutting edge induced by thermal shock during an interrupted turning operation. The cutting edges were examined optically for thermal cracks after every one-minute length of cut. Thermal cracks generated AE pulses with higher amplitude and longer duration than other pulse events observed. By comparison, the durations of AE pulses from tool chipping, discussed earlier, are short. The amplitudes of the AE pulses from thermal cracks are much higher than the expected amplitudes of AE pulses from tool breakage events with equivalent size of the cracked surface area. Kakino *et al.* [30] postulated that one possible cause of the difference in length of pulses might be a slower propagation rate of the thermal cracks than of the mechanical cracks. The total surface area of the thermal cracks was measured after the edge was carefully cleaned, and this area was compared with the total AE energy represented by the sum of the area of thermal crack AE peaks from the average AE amplitude–time curve. On a log–log plot, the integral sum of AE energy, according to these data, increases linearly with the total area of the thermal cracks. This group also mounted a pair of strain gauges on the tool holder and simultaneously monitored both the cutting force and the AE signal. By comparing these signals, it was shown that thermal cracks began about 9 to 10 mm into each cut at a cutting speed of 180 m min^{-1}. The power spectrum of the AE signal with thermal crack pulses had much higher amplitude over a frequency band of 100 to 300 kHz than signals without the thermal crack pulses. This group also observed a similar power spectrum change with a broken edge. It is interesting to note that Inasaki and Yonetsu also studied the AE power spectrum and concluded that the same 100 to 300 kHz frequency band AE signal was most sensitive to tool wear. They used a 300 kHz high-pass filter to suppress the tool wear signal and enhance the AE signal from tool fracture and cracking, as described earlier.

Lan and Naerheim [31] studied AE from machining SAE 4340 steel and a titanium–6Al–4V alloy. In addition to confirming various observations reported by earlier investigators, they also observed a rather marked effect of the chemistry of the cutting fluid on the AE signal. When carbon tetrachloride was injected into the cutting zone in the middle of a cut, the average AE RMS amplitude dropped significantly at that point. The authors also pointed out, from their observations of the AE signal from machining the Ti–6–4 alloy that the RMS AE signal fluctuates rapidly as the edge wears. Analysis of the statistical properties of the RMS AE signal demonstrated that the kurtosis (the sharpness of the peak relative to a normal distribution) increases rapidly as flank wear becomes significant. The peculiar nature of the AE from a worn tool cutting titanium, according to these investigators, permits detection of the unusual wear scar developing on the tool nose. The fluctuating pattern of the AE signal amplitude correlates closely with the corresponding pattern of surface roughness.

Dornfeld and Pan [32] also reported that the chip forms, such as continuous and discontinuous, can be determined from monitoring the AE pulse event rates. They proposed a linear discrimination function, based on the cutting parameters and the event rate of the RMS of AE, for chip-form monitoring applications. Dornfeld and Lan [33] observed that the AE event rate increases gradually at first with increasing feed rate, but the event rate remains relatively constant above some critical feed rate. This observation is consistent with the reported effect of the feed rate on the chip curl radius and the chip breaking frequency. However, further examination is needed to understand why this effect of the feed rate on the chip–tool contact geometry, and hence on the AE processes, did not influence the experiments by Inasaki and Yonetsu. Inasaki and Yonetsu [29] observed no apparent effect of the feed rate on the average AE level, as discussed previously.

Dornfeld [20] also reported a strong effect of instabilities of the cutting state, or chatter, on the AE signal, both in the time domain variation of the signal amplitude and in the power spectrum of the AE signal. The amplitude of the high-frequency portion of the power spectrum increased significantly, compared with the signal from stable machining conditions, when the cutting process became unstable. It should be noted that a similar change in the power spectrum was observed by many other investigators when their tools were worn severely, broken, thermally cracked, or damaged. However, no plausible physical mechanisms explaining the particularly fast increase of AE energy in the higher frequency portion of the power spectrum upon cutting edge damage has been proposed.

A very interesting study of the basic chip-formation mechanisms and the possibility of monitoring the built-up-edge break-up process has been reported by Uehara [34]. Uehara postulated that the metal undergoing deformation in the primary and the secondary shear zones is in a fully plastic state, and the ratio of stress increment to the corresponding strain increment at this state will be very low. This plastic zone, therefore, will reflect or dampen any incident elastic waves, such as the AE signal. By monitoring the AE signal from the tool and the workpiece sides separately, Uehara expected to distinguish the AE events occurring at different sides of the chip–tool interface. Four different metals, 0.45% C steel, 304 stainless steel, Ti–6Al–4V, and 40/60 brass were machined on a lathe. The AE signal was monitored with one sensor attached on the end of the workpiece inside the chuck and another on the tool holder. The frequency band of the monitored signal was from 100 kHz to 1 MHz. A dynamometer was used to monitor the forces.

Uehara [34] reported several interesting experimental results from this study. His results confirmed his original postulation that the AE signal monitored from the workpiece side would be different from the signal detected by the sensor on the tool. In the case of carbon steel, he observed that some burst signals appeared on both sensors, but some appeared on only one or the other. He explained that the burst events are caused by the break-up of the built-up edges and that if the break-up occurs at the tip of the tool so that one part is carried away by the surface over the tool flank and other part is removed by the chip over tool rake face, signals from both AE sensors will show the burst events. However, if only a small portion of a built-up edge is broken up under the cut-line and carried away by the workpiece, but the main part stays on, only the sensor on the workpiece will see the AE burst. On the other hand, if only a small portion of the built-up edge on the rake-face side breaks up, only the sensor on the tool will see the AE burst.

Stainless steel, hard brass, and titanium alloys form heavily segmented chips, and Uehara observed cyclic variations of cutting forces corresponding to these chip segmentation cycles. The AE signals from the sensor on the tool also showed periodic pulse events approximately equivalent to the cycles of the fluctuating cutting force, indicating that the chip segmentation process causes these AE bursts. However, the AE signal from the sensor on the workpiece did not show corresponding pulse events. Uehara, therefore, theorized that AE bursts result from stick–slip events at the chip–tool interface, and that the signal is blocked from reaching the sensor on the workpiece by the primary shear zone. When each segment of the saw-tooth-shaped segmented chip is removed from a workpiece, a sloping shoulder remains. The cutting edge, therefore, cuts into an inclined plane on each cycle of cut, and accordingly, the corresponding shear angle also continuously oscillates. This causes fluctuation of the sliding speed of the chips, and the intermittent stick–slip motion at the chip–tool interface becomes the source of AE bursts.

3. Discussion

As predicted, all physical actions of cutting, regardless of rate and size, are sources of AE events. Many investigators confirmed experimentally that all these AE events can be detected by suitable sensing devices. Most of the researchers also advanced theories explaining their experimental observations, but the basic cause–effect relationships still need further investigation. There are many interesting questions to be answered. The most important question relates to the basic mechanisms by which various factors affect the average intensity of the AE signal. Only the strong effect of cutting speed, hence the strain rate, has been confirmed by all investigators. Because no physical model of the AE source mechanisms explaining the powerful effect of the cutting speed has been developed, specific experiments addressing this question are necessary. For example, simple experiments, such as machining materials with different strain-hardening exponents and strain-rate sensitivities and studying the rate of the average AE intensity increase with speed, should provide information concerning the effect of the yield strength and work-hardening characteristics on the AE signal.

All parameters influencing machining conditions have shown some effect on the characteristics of AE, but various publications often reported conflicting results. A good example of this is the effect of feed and depth-of-cut on the average AE intensity. Apparently, most researchers who studied carbon steels or low-alloy steels observed very little change, or only a minor effect of these cutting parameters on the average AE intensity, and concluded that these two parameters have no significant effect on AE. However, some significant effect of depth-of-cut on the average AE has been reported for machining SAE 4340 steel. It seems that the intensity of AE from machining low-strength metals shows little or no dependence on the feed and the depth-of-cut, but these parameters become significant for the machining of high-strength alloys. The relationship between the AE mechanisms of machining and the basic strengthening mechanism of alloys needs to be explored. That the yield strength of workpieces would influence the average AE output has often been postulated, mainly based on the experiences of the AE from metal deformation processes, but no experiments exploring this relationship for machining processes have been reported. Workpiece materials with controlled chemistry but with varying degrees of heat treatment should provide useful information regarding the effect of yield strength.

One particularly interesting, and also somewhat puzzling, result in observations by Kannatey-Asibu and Dornfeld [21] with AA 6061–T6 aluminium and SAE 1018 steel, and later by Lan and Naerheim [31] with SAE 4340, is that the average AE RMS increases with increasing rake angle. All other cutting energy-related parameters, such as forces and cutting horsepower, generally decrease with increasing rake angle. For an approximate correlation between the measured average AE output and the estimated energy of cutting, Kannatey-Asibu and Dornfeld needed a proportionality factor adjusted with the sine of the rake angle (see Equation 2). If these results are confirmed in the future, an understanding of the basic physical causes of this phenomenon might provide insight into the basic metal-cutting AE mechanisms, and explain how some of the cutting energy dissipates as lattice vibration energy. The effect of the total volume as well as the thickness of the primary shear zone also needs investigation because the actual shear strain rate changes, depending upon the thickness of the shear zone. If the strain-rate dependence of AE intensity is a stronger function than the strain-rate dependence of the cutting energy, then any change of shear zone geometry will have an effect on the proportionality constant, relating the AE energy to the total cutting energy. If this is true, increasing rake angle is expected to have an increasing effect on the AE intensity, because the thickness of the shear zone will decrease as a result. The effective shear strain rate increases with decreasing thickness of the shear zone.

Other points that need further study are the respective contributions to the AE output by the primary and secondary shear zones, and the variation of these contributions with rake angle. The AE from the primary shear zone should be very sensitive to the physical properties of the workpiece, but the extent to which the same is true for the secondary shear zone, consisting primarily of already heavily deformed materials, needs further study. Future studies also should include the experimental relationship between the total energy necessary for machining and the corresponding average AE output.

Until these questions concerning the relationships between the micromechanics of the chip-making processes and the energy of the AE signal are answered with reasonable certainty, development of any general tool wear monitoring schemes utilizing the degree of average AE intensity variation in relation to the tool wear will require very difficult, and perhaps tedious, calibration methodology.

Reports on the frequency-domain analysis of AE signals are sketchy, and none of the published reports provides detailed procedures applied for the calibration of sensors and systems. However, the power spectra from worn tools, broken tools, and thermally cracked tools show a significant increase of the energy content in the high-frequency band of signals. It may be true that the energy over the entire frequency range is increasing in the same proportion, but because of the sensitivity of the detection system, only the increase of the high-frequency signal is detected. The lower frequency bands are generally very loud, and the magnitude of increase as a fraction of the total amplitude in this frequency range may be relatively insignificant. In order to apply the frequency domain information effectively for a tool condition monitoring system, much more systematic experiments, using well-characterized sensors and electronic systems, will be needed. In addition, careful investigation of potential noise sources in various frequency bands of the signal (particularly when the prime character of the signal of interest is burst-type noise) is needed for a proper analysis of signals. No such concerns were shown in any past reports.

Because many different physical events useful for correctly diagnosing the cutting conditions can be related to the pulses of the AE signal, it is necessary to characterize the pulses and to determine the feasibility of identifying individual pulses related to specific physical events. According to earlier investigations, the relationship between the total count of AE pulses over a threshold level and tool wear may be more reliable than that between average AE energy level and tool wear, provided that the threshold energy level is properly chosen and the system is accurately calibrated. Further studies of the basic sources of those pulses of primary importance to this particular scheme of wear monitoring should provide a more intelligent basis for determining the threshold level.

The density of pulses increases with increasing wear up to a point, then remains relatively unchanged. However, continuation of tests beyond the end point of the published data might have shown further change in the density. Tool wear generally develops in three stages [35]. At the beginning, tools tend to wear rapidly up to a point; then the wear proceeds at a steady, but somewhat slower, rate. Toward the end of tool life, or when the size of wear land exceeds some critical point, wear rate increases rapidly again. Some of the published results indicate that the wear tests might not have proceeded far enough to reach the third, rapidly wearing, stage. Furthermore, if the count rate above a certain flank wear indeed stays constant up to the end of tool life, the total count of events beyond the initial wear should increase as a linear function of the cutting time. If this is proved to be true, any monitoring device using the event count method needs to monitor only up to the time when a meaningful average steady-state count rate can be established. Further studies are needed to clarify these points.

Uehara's observation [34] that there is a significant difference between the AE signal monitored from the tool post and from the workpiece needs further verification. If Uehara's hypothesis is proved correct, it suggests many potentially interesting possibilities. For example, one should be able to identify the location of the sources of some specific pulses by monitoring signals from the two sensors located on the tool holder and on the workpiece or its holding fixture. Uehara's theory that the AE signal monitored through the sensor on the tool holder reflects the physical events occurring predominantly along the tool–chip interface also needs further verification.

4. Summary

Several key topics requiring further studies exist. These are:

1. Better physical interpretations of the proportionality constant relating the average AE output to the total energy consumed for the chip-making process.
2. More systematic evaluation of the effect of strain rate sensitivity, the yield strength of workpieces, and general microscopic deformation processes on AE.
3. Respective contributions of the shear deformation in the primary shear zone and the sliding interaction at the tool–chip (rake) and the tool–workpiece (flank) interface, for different materials on AE.
4. Effect of the rake angle, the thickness of the shear zone, and the real shear strain rate on AE.
5. Effect of the depth-of-cut and the feed per revolution on the volume of the shear zone and the area of tool–chip contact, and their influence on AE.
6. Relationship between the average AE output and the specific cutting power for a broad range of materials and cutting conditions.
7. Relationship between the AE pulse density and flank wear for the range of very large flank wear.
8. The source mechanisms of very large AE pulses, and the general relationship between the AE pulses and tool wear.
9. Verification of the observations that the AE signal monitored from the tool holder can be significantly different from the AE signal monitored from the workpiece.

It can be stated that many interesting possibilities have been raised concerning the application of AE for the in-process monitoring of metal-cutting processes, but the lack of convincing explanations for the physical causes of many of these observations, as well as a number of inconsistencies apparent among observations by different groups, indicate the need for further research. Careful verification and better interpretation of the observations are needed before any practical system can be developed systematically.

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