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Using Acoustic Emission to Predict Surface Quality

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Acoustic emission (AE) is harnessed in machine process monitoring today, predominantly using root mean squared (r.m.s.) AE signals to monitor tool wear and breakage. In turning, there may be a link between acoustic emission and the quality of surfaces being turned. This is examined by correlating parameters extracted from raw acoustic emission data with surface roughness (R_a) for various cutting conditions. Comparing measured and theoretically modelled AE proves useful in the implementation of a surface quality monitor. When this comparison is itself correlated with a similar comparison between the measured and modelled R_a, a relationship between AE and surface roughness is uncovered.

Keywords: Acoustic emission; Monitoring of machining; Signal analysis; Surface roughness

1. Introduction

Acoustic emission is just one of a number of quantities which can be monitored during machining operations in order to provide process information to the machine operator. Other parameters that are sometimes used to provide such information include machine tool power consumption, torque, force and vibration. Optical, tool temperature, electrical resistance and radioactive methods have also been investigated [1–3]. Acoustic emission is generated at the tool/workpiece/chip interfaces and, hence, is directly influenced by changes in the cutting process, making it suitable for process condition monitoring. An advantage in the use of AE as a process monitor is that the frequency range of the acoustic emission is much higher than that of machine vibrations and ambient acoustic noise, and, hence, with the use of a high-pass filter, AE data can be readily obtained.

Acoustic emission based tool condition monitoring (TCM) systems have been available for approximately 15 years, with most using the analogue root mean square of the signal to monitor tool wear or detect breakages. The principles behind the operation of these systems are based on empirical studies, which have shown acoustic emission signal power to increase with tool wear owing to increased friction effects [4]. In the event of catastrophic tool breakage there is a large release of AE energy at fracture before the acoustic emission signal drops to background noise levels [5].

This work attempts to take the state of the art in AE monitoring of cylindrical turning a step further by using the acoustic emission signals to make an in-process estimation of the surface quality, in terms of surface roughness of the workpiece. Relating the surface condition to the monitored AE takes the traditional acoustic emission TCM system to its logical next step, as, tool breakage and dangerous failures apart, tool condition is generally of interest only insofar as it affects the surface in production. To this end, the signal analysis or feature extraction used with acoustic emission signals is examined and improvements based on time domain analysis are investigated.

Measurements of R_a and acoustic emission for a range of cutting speeds and feeds are used as the basis for the proposed system. For each cutting condition, the theoretical R_a is calculated using a geometric model. An existing model for acoustic emission from the turning process is modified to provide an estimate of the AE signal levels expected. This provides an equivalent standard value relating the measurements of AE and R_a for different cutting parameters. A correlation between surface roughness and acoustic emission signal is achieved by relating each measured R_a and extracted AE parameters to the values predicted by the models.

2. Theoretical Background

2.1 Acoustic Emission Background

The ASTM defines acoustic emission as “the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localised sources within a material, or the transient elastic waves so generated” [6]. Other terms for this phenomenon are stress wave emission and microseismic activity.

Förster and Scheil published the first experiments specifically designed to detect AE in metal in 1936 [7]. By the late 1960s, AE was being applied in the field of non-destructive structural stress testing, particularly of pressure vessels [8]. Amongst other uses of acoustic emission today are crack detection in bridges and hydroelectric dams, failure detection in composite laminates and as a monitor in metal cutting, dressing of grinding wheels and welding processes [9].

The elastic waves of AE produce tiny displacements on the surface of the transmission media, and these waves can be

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detected using specialised highly sensitive piezoelectric devices [10]. Most of these devices respond with a particular characteristic to excitation in the 50 kHz to 1 MHz frequency band. The bandwidth is dependent on the particular device, and some form of coupling medium (usually grease) is required to transmit the waves to the sensor. Most sensors are supplied with charge amplifiers and electronics, which output the acoustic emission as a voltage signal to the monitoring system.

2.2 Acoustic Emission in Turning

There are four major mechanisms generating acoustic emission in turning; material deformation, friction and emissions from chip breakages (see Fig. 1) and collisions between chips and the workpiece or tool. In the primary cutting zone, the bulk deformation of the work material to form the chip, and also crack growth mechanisms are recognised sources of AE [11]. In the secondary zone, sliding friction between the chip and tool causes acoustic emission. Sliding friction in the tertiary zone between workpiece and tool flank adds to the acoustic emission from the process. Chips themselves are another source of AE, chip fracture and chip–tool and chip–workipece collisions can contribute considerably to the total acoustic emission signal, depending on material and cutting conditions. Of the AE sources listed, the emissions from material deformation and those generated by friction effects at the workpiece are of most importance in monitoring.

Acoustic emission signals emitted in turning have as a general form, a continuous background component which is associated with the bulk deformation of the material and friction effects, and discrete "burst" type components which are superposed on the former. The "burst" events are generally associated with chip breakage and collisions between chip and workpiece/tool [11].

Kannatey–Asibu developed a model describing the AE generated by plastic deformation in the primary cutting zone and by friction in the secondary cutting zone based on the assumption that the power of the acoustic emission signal can be related to the power which produces plastic deformation [11]. If the material is subjected to a constant stress σ and strain rate $\dot{\epsilon}$, which can be assumed to be the case in machining, the work rate associated with plastic deformation can be expressed as Eq. (1), where V = volume of material deformed.

$$\dot{W} = \sigma\,\dot{\epsilon}V \tag{1}$$

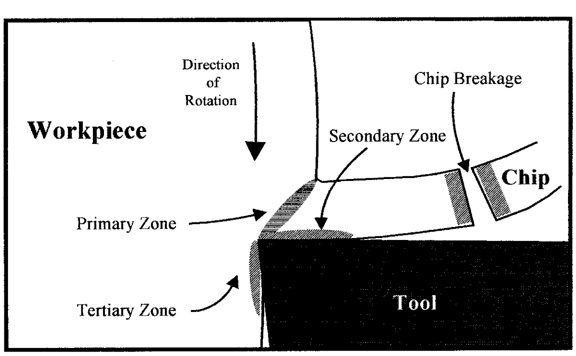

Fig. 1. Sources of acoustic emission in turning.

The power producing plastic deformation depends on the rate of deformation, the applied stress, and the volume of material involved. To link this equation with the r.m.s. acoustic emission, it has to be assumed that the ratio of plastic work of deformation that produces acoustic emission to that which generates more dislocations is constant. The power of the AE signal, (r.m.s.)^2, is directly equated to the power producing plastic deformation. The r.m.s. of a signal is defined in Eq. (2), where ΔT = average time period, and $V(t)$ = signal function.

$$V_{\text{rms}} = \sqrt{\left(\frac{1}{\Delta T}\int_0^{\Delta T} V^2(t)\mathrm{d}t\right)} \tag{2}$$

One conclusion of Kannatey–Asibu's work was that the AE_{rms} is proportional to the square root of the cutting speed. Lan [12] developed this model further, he included a term for the acoustic emission generated in the tertiary cutting zone owing to friction at the tool flank/workpiece interface. The model is modified to take account of the geometry of 3D cutting but continues to assume that plastic flow occurs under plane strain. This leads to the following equation, which includes a factor for signal noise:

$$AE_{\text{rms}} = C_1\left[\tau_k a_p v_c\left(C_2\frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)}f + C_3\frac{(l+2l)\sin\phi}{3\sin\kappa_r\cos(\phi-\alpha)} + C_4 w\right)\right]^{\frac{1}{2}} + Noise_{\text{rms}} \tag{3}$$

where τ_k = shear strength of workpiece material, a_p = depth of cut, v_c = cutting speed, α = rake angle, ϕ = shear angle, f = feed per revolution, l = chip-tool contact length, l_1 = length of sticking zone in secondary cutting zone, κ_r = cutting edge angle, w = average flank wear land, C_1, C_2, C_3 and C_4 are factors of signal attenuation. In the machining tests here, new tungsten carbide tool inserts were used which had a TiN outer coating and a chip former. It can therefore be assumed that the chip–tool contact length (l) and the length of the sticking zone (l_1) remain constant for the cutting conditions used, and that the average flank wear land (w) is negligible. The dependence of the shear angle on the different cutting parameters is also neglected. The $Noise_{\text{rms}}$ term is found by measuring the AE_{rms} level while the machine tool is running, prior to cutting.

Thus, for a given cutting geometry, the above model can be simplified and expressed as Eq. (4).

$$AE_{\text{rms}} = C_5[a_p\,v_c\,(C_6\,f + C_7)]^{\frac{1}{2}} + Noise_{\text{rms}} \tag{4}$$

This equation states that AE generation in turning is proportional to the square root of cutting speed. Other research suggests that AE is proportional to v_c or the square of v_c [13]. This model is modified to account for such a variation in the strain rate dependency in the primary cutting zone by introducing a material related exponent n, to Eq. (5). Lan [12] used a similar material-dependent factor in his work, but also applied it to a_p and f by replacing the exponent of $\frac{1}{2}$ in Eq. (3) with m.

$$AE_{\text{rms}} = C_5(C_6 a_p\,v_c^n\,f + C_7 a_p v_c)^{\frac{1}{2}} + Noise_{\text{rms}} \tag{5}$$

Hence, with knowledge of the basic cutting parameters (depth of cut, feedrate and cutting speed) the unknowns are reduced to the constants C_5, C_6, C_7, n and the $Noise_{\text{rms}}$ term – each of which can be estimated empirically. This allows the AE_{rms} level to be predicted for given cutting conditions.

2.3 Surface Generation and Measurement

In turning, the factors which influence the surface generated include cutting parameters (v_c, a_p, f), chip/tool interaction and dynamic machine effects. Surface roughness is obviously affected by feed and depth of cut, but cutting speed (v_c) also has an influence, with surface roughness generally decreasing as v_c increases (more markedly at lower speeds) [14]. The chip removal mechanisms, and hence surface generation, are also affected by chip/tool interactions, such as sticking or slipping on the rake face. Dynamic machine effects such as vibration and chatter will also influence the surface roughness and appearance of the workpiece. In any attempt to analyse and predict surface quality of the workpiece from acoustic emission, it is these effects that must be determined and/or isolated.

The centre line average roughness of a surface (R_a) is one of the most common measures of surface roughness and is easily obtainable using stylus profilometry. The expected surface profile in turning can be established geometrically from the kinematics of the machine tool, the tool geometry (such as tool nose radius and back clearance angle) and the feed. Hence, provided that this tool and cutting information is to hand, a theoretical R_a surface roughness value can be predicted before cutting.

3. Experimental Work

Machining tests were carried out on a Fanuc controlled Daewoo Puma 4–3A NC turning centre. This lathe does not have a tailstock. Tungsten carbide finishing tool inserts were used to turn free machining leaded mild steel. These tool inserts (CNMG 12 04 04 PF 4015) are coated with titanium nitride over a layer of aluminium oxide. Both coatings are applied by chemical vapour deposition over a thermal resistant substrate. The work material, EN1APb, was chosen for ease of machining, allowing for generation of surfaces of varying quality without the use of cutting fluids. The free machining nature of this steel and the choice of tool insert enabled tool wear to be kept to a minimum throughout the experiments. Tool inserts were changed regularly (for each test specimen) in order to keep tool condition as constant as possible. SEM analysis of the tool inserts after the machining tests showed wear was indeed negligible. Each machining specimen was 150 mm in length, and was used for cutting of five 20 mm test surfaces along the specimen at differing feedrates. Five speeds and five feedrates were chosen for the tests, each feed to be cut at each speed. The speed and feed values which were used in machining were chosen around the optimal values as recommended by the tool insert manufacturers ($v_c = 350$ m min^{-1}, $f = 150$ μm) and were varied either side of this value with a view to producing measurable variations in surface finish. The cutting conditions are presented in Table 1. Each of the 25 tests was repeated four times. The cutting location, for each particular set of parameters, relative to the chuck was varied for each set of trials. This serves to reduce the influence of workpiece geometry and associated vibration effects on the process. Depth of cut (a_p) was fixed in order to limit the amount of testing data produced (over 10 MB per test).

Surface measurement of the test specimens was performed using a portable stylus profilometer. This calculates a centre line average roughness (R_a) and outputs a voltage signal representing the profile of the surface, which was then converted to digital form and stored on a personal computer.

Table 1. Experimental cutting conditions.

Parameter	Value(s)	Units
Speed (v_c)	100, 200, 300, 350, 500	m min^{-1}
Feed (f)	30, 60, 100, 150, 200	μm
Depth of cut (a_p)	0.5	mm
Material: Mild steel		
Tool: CNMG 120404 PF 4015		
Cutting fluid: None		

The test AE measurement equipment consisted of a narrowband (100–400 kHz) AE Sensor (Kistler Instruments 8152A11) which was mounted on the toolholder (see Fig. 2). The design of the sensor housing means that it can be mounted close to the acoustic emission source and also ensures a nominally constant coupling pressure between toolholder and sensor. A light coating of petroleum jelly was applied under the sensor to ensure good acoustic emission coupling. The output from the sensor was converted to voltage, amplified and bandpass filtered (100–1000 kHz) using a standard module supplied with the sensor. The filtered signal was then passed through a tuneable filter for subsequent bandpass filtering from 100 to 400 kHz, using fourth order Butterworth filters, to further isolate the AE signal from noise. The filtered signal was then sampled at 5 MHz using a data acquisition card fitted to a Pentium Pro computer. The signals were recorded in 1 MB sections, five of which were recorded over each test (totalling 0.5 s of data per test). All test data were processed and analysed using the MATLAB analysis and visualisation software package with some further analysis and plotting achieved with MS Excel.

4. Results and Discussion

As can be seen from Figs 3 and 4 the acoustic emission signal contains components of continuous and burst nature. Bursts are also associated with the breakdown of a built-up edge (BUE), but the occurrence of significant BUE at these cutting conditions is unlikely. Figure 3 shows a low speed and low feed ($v_c = 100$ m min^{-1}, $f = 30$ μm) AE signal which can be described as a continuous signal. Figure 4(a) shows AE recorded during high-speed and high-feed machining (v_c = 500 m min^{-1}, f = 200 μm) and consists of burst events super-

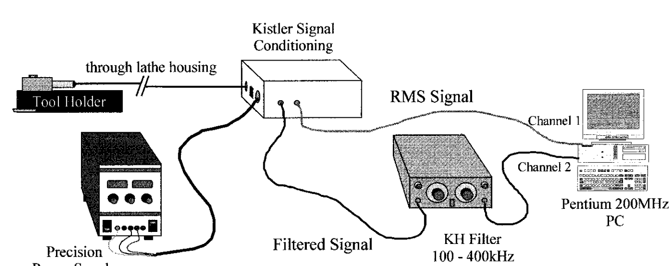

Fig. 2. Schematic of AE testing set-up (turning centre is not shown).

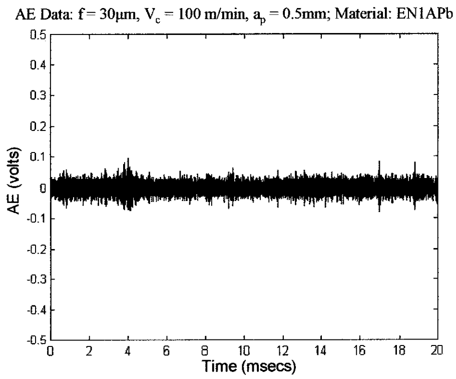

Fig. 3. Acoustic emission data: predominantly continuous acoustic emission (low cutting speed and feed).

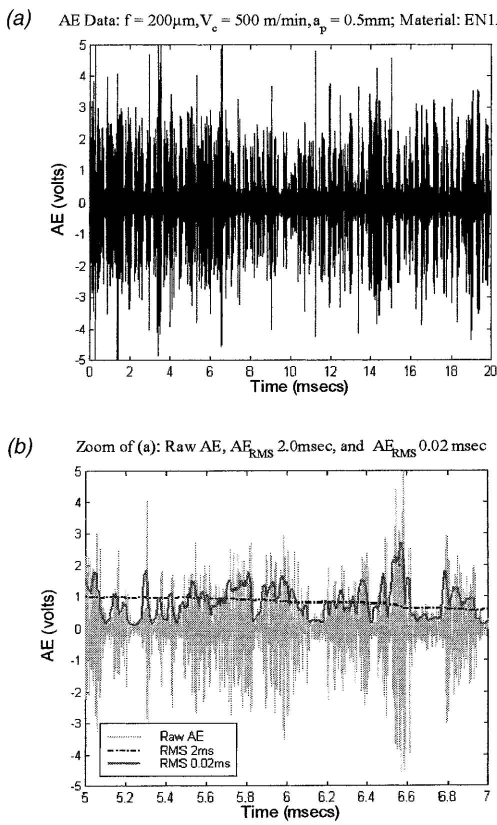

Fig. 4. Acoustic emission data: (*a*) AE with burst events (high cutting speed and feed); (*b*) subset of data showing slow r.m.s. ($\tau = 2.0$ ms) and fast r.m.s. ($\tau = 0.02$ ms).

posed onto a continuous signal. Each of the plots contains 100 000 data points.

The r.m.s. AE level (AE_{rms}) is by far the most common measure of acoustic emission used in the context of tool condition monitoring (TCM). In TCM systems and much previous AE research, it is the case that mean r.m.s. values are generally used to quantify the r.m.s. level [15]. However, the AE_{rms} signal level can be increased by the occurrence of bursts, which are believed to be predominantly due to chip fracture and impacts. Bursts will cause the AE_{rms} signal to "ride high" if the time constant (τ) of the r.m.s. such as to spread the effect of one burst into the next (Fig. 4(*b*)). Blum [16] used a quantity called AE-mode, the most common r.m.s value in a given period, in an effort to reduce the influence of the superposed burst events on the AE parameter used for process monitoring.

However, the time constant of the r.m.s. can be reduced so as to allow the r.m.s. to decrease to the continuous AE level between bursts (e.g. $\tau = 0.02$ ms). A minimum value of this r.m.s. is taken and the effect of the bursts on the overall r.m.s. parameter is greatly reduced. In reality, a minimum value is not effective as it is liable to distortion by one data point alone. To eliminate this problem, the AE value is taken as the value below which 20% of the AE_{rms} data points lie. This quantity is referred to here as "AE_{rms20}". The 20% value was chosen following examinations of sorted r.m.s. data sets with respect to the original data. It is seen from Figs 5(*a*) and 5(*b*) that the AE_{rms20} value increases with speed, but it does so less sharply than does the mean AE_{rms}, owing to the influence of the bursts on the latter. It is also noted that the AE_{rms20} actually decreases with feed.

This is contrary to the model outlined previously (Eqs (1), (2) and (4)) which predicted that AE would rise with the square root of feed. In fact, much empirical research shows trends of AE decreasing with feed [16,17]. It may be that increasing ductility of the workpiece at higher cutting temperatures, associated with larger feeds, results in a decrease in the work of plastic deformation and the corresponding AE. This suggests that such variations in ductility of the workpiece must also be considered if the AE model is to be improved further. Also the AE_{rms20} is less likely to be influenced by any larger chip breakage and collision burst events associated with increasing chip thickness. Thus, the relative isolation of the AE_{rms20} quantity from burst events, along with possible ductility issues, result in a decreasing AE_{rms20} with feedrate.

It can be seen from Figs 5(*c*) and 5(*d*), that the feedrate dominates the R_a values, as expected. It is also noticeable that the roughness values depart considerably from the theoretical values at lower speeds owing to increased rubbing and "spanzipfel". From the corresponding plots for the AE_{rms20} parameter (Figs 5(*a*) and 5(*b*)), it is seen that as with R_a, the AE_{rms20} increases sharply from the predicted values at lower feeds. The relationship between *AE* deviations and R_a deviations is seen to be similar with changing feeds. The results above are presented as percentage deviations from the modelled R_a and AE_{rms20} in Fig. 6. These plots give a clearer view of the relationship between the deviations in measured *AE* and R_a from their modelled values.

The *AE* and R_a data above is in general agreement with the theory. In the task of relating surface quality to *AE* levels or features, it was seen that the mean AE_{rms} is highly dependent on cutting speed, while the R_a values are more influenced by feedrate. This implies that a direct correlation of AE_{rms} and R_a is difficult to achieve.

The AE_{rms20} values are less influenced by cutting speed than mean AE_{rms}, owing to the decreased effect of burst activity. Notably, the AE_{rms20} parameter is more dependent on feed than is the mean AE_{rms} value, and it is seen to decrease with increasing feed. This decrease is not as obvious from the mean AE_{rms}, owing to acoustic emission bursts which inflate the

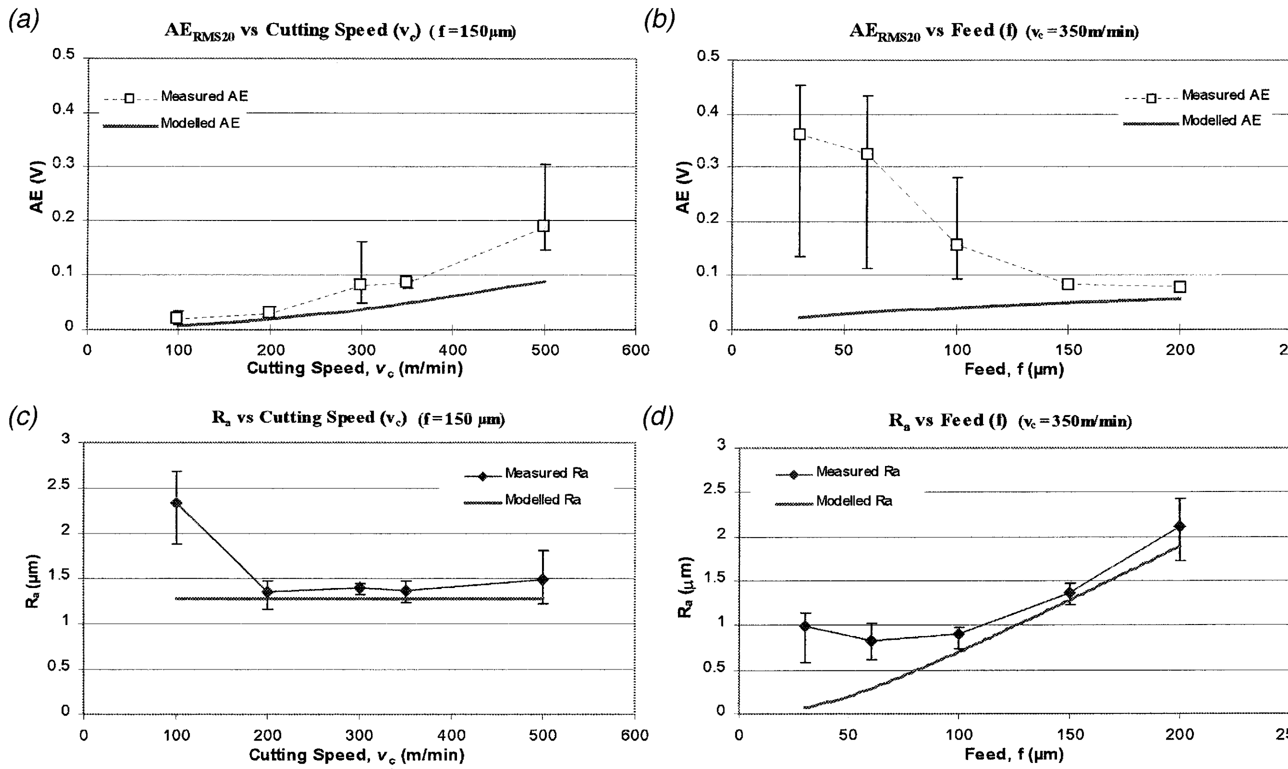

Fig. 5. (*a*) and (*b*) AE_{rms20} measured and modelled; (*c*) and (*d*) R_a actual and modelled (all data points are means of four repetitions).

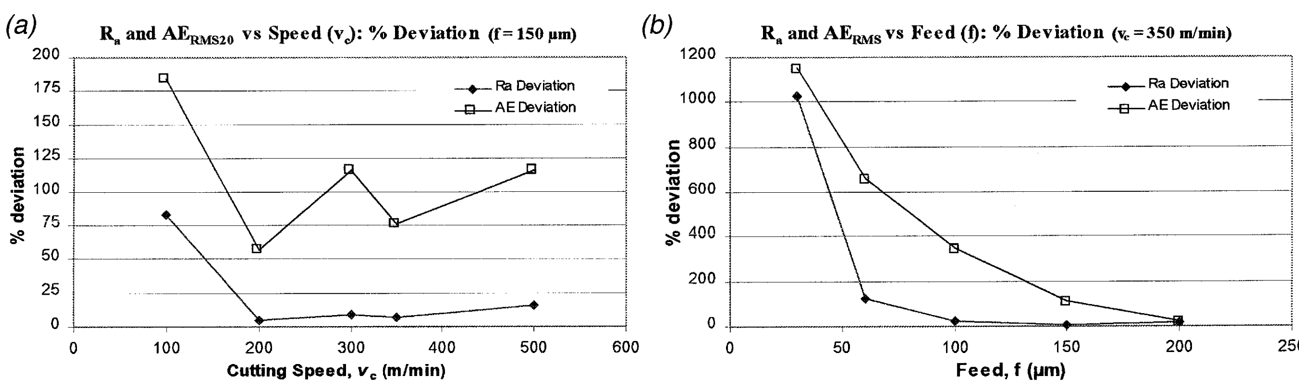

Fig. 6. Percentage deviations from measured R_a and AE_{rms20} values to modelled values.

mean AE_{rms} at higher feeds. It may be that the AE_{rms20} decreases with feedrate, despite the increasing levels of bulk deformation, owing to the changing work rate of plastic deformation.

The correlation between the deviations in theoretical and measured acoustic emission and surface roughness (R_a) shows some very promising trends. Comparing Figs 5(*a*) and 5(*b*) with Figs 5(*c*) and 5(*d*), it can be seen that the measured acoustic emission level is above that which is predicted from the model, and that the surface roughness is also above the modelled R_a value. The correlation is good at medium and high cutting speeds and feeds. At lower feeds, the proportionality is somewhat stretched, owing to the nature of the two models. Neither of the models takes into account the effects on R_a and on acoustic emission of the increased friction, pitting, ploughing and squeezing that occur at lower feedrates and cutting speeds.

The above correlation can only be implemented if an *AE* model is established for a specific turning operation, therefore the constants and the non-cutting signal-noise level must be established (Eq. 5). C_5, C_6, C_7, and n are established from empirical data, while $Noise_{rms}$ is simply the r.m.s. value of the AE detection system when the machine is running, but no cutting is taking place. Simple geometry of the tool insert must also be known, along with cutting speed, feed and depth of cut in order to model R_a. The latter cutting parameters are obtainable from the NC controller of the turning machine. Once the two theoretical curves are generated, and the relevant points on the curves, according to cutting conditions, established, a workpiece which produces *AE* above a given percentage of the reference model value can be assumed to have a correspondingly high surface roughness.

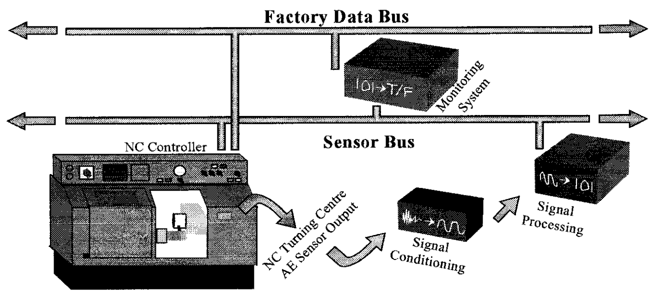

Fig. 7. Schematic of proposed industrial implementation of an acoustic emission surface quality sensor.

Although this finding is significant in itself, further analysis of the acoustic emission signals would be required in order to increase the reliability of the system – to protect against irregular *AE* values giving inconsistent results. From the point of view of integrating an acoustic emission surface quality sensor in an industrial situation, it is most likely that it would find use as part of a factory data bus system. A schematic of such a system implementation is shown in Fig. 7.

5. Conclusions

The "minimum" constant value of r.m.s. acoustic emission, "AE_{rms20}" is a more useful quantity of acoustic emission for providing information on the cutting mechanisms than the traditional mean or maximum measures of AE_{rms}. This is attributable to the fact that it is less influenced by the occurrence of burst events which are most often due to non-cutting events such as chip breakage and chip collisions. It is seen that a positive correlation exists in the deviations between modelled and measured values of *AE*, and those from modelled and actual surface roughness (R_a). This correlation can be employed to predict the surface roughness of a workpiece while it is still in production, if basic process information is available. Tool insert geometry (nose radius and back clearance angle) and cutting information are required (v_c, a_p, f), although the influence of depth of cut on the acoustic emission has yet to be firmly established.

Higher than predicted acoustic emission levels are due to factors such as increased squeezing and rubbing at the tool/workpiece interface. These factors also lead to higher than geometrically predicted surface roughness. The varying accuracy of the correlation may be due to the changing influences of cutting temperature, rubbing, surface pitting, ploughing, and other deformations as turning parameters vary, and also the dynamic effects of the machine tool on the turned surface. Research into these findings is continuing, with a view to building a pseudo-real-time PC based surface quality monitoring system, which can then be optimised and ultimately implemented as a real-time surface quality sensor system.

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