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Real-time tool wear condition monitoring in turning

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A new method to monitor tool wear condition in real time using feed-motor current measured with the aid of inexpensive current sensors installed on the AC servomotor of a CNC turning centre is presented. To achieve this, the feed drive system model is analysed, the feed-motor current is measured, and the relations between feed-motor current, cutting force, and tool flank wear are addressed. The functional dependence of the feed-motor current on tool wear is then expressed in the form of a difference equation relating variation in the feed-motor current to tool flank wear rate. The computerized system automatically compares successive feed-motor current and determines the onset of accelerated tool wear in order to issue a request for tool replacement. Experimental results show that this method of tool wear condition monitoring is effective and industrially applicable.

1. Introduction

It is very important to develop a reliable and inexpensive intelligent monitoring system for use in cutting processes. A successful monitoring system can effectively maintain machine tools, cutting tool and workpiece. Research to date has shown that there are four parameters, including cutting force, acoustic emission, motor power/current and vibration, which could be used to monitor tool wear condition in real time during turning. Force-based techniques and acoustic emission (AE) are, however, the two primary methods.

Cutting force is one important characteristic variable to be monitored during the cutting processes (Koren *et al.* 1991, Park and Ulsoy 1992, Ravindra *et al.* 1994, Kumar *et al.* 1991). Research results show that tool breakage, tool wear and workpiece deflection are strongly related to cutting force (Stein *et al.* 1986, Lee *et al.* 1995). Commercial dynamometers have been used to measure cutting force accurately. Although different types of dynamometers are available for different cutting applications, however, the reduced stiffness of machine tools, leading to chatter and dimensional error, lack of overload protection and high cost limit their application (Altintas and Dong 1990).

Acoustic emission (AE) refers to very high frequency stress waves generated by the sudden release of energy during deformation of materials. When metals are cut or fractured, AE is linked to the plastic deformation process occurring during chip formation due to the interaction between workpiece and cutting tool. Continuous AE signals generated during metal cutting have been successfully applied to tool

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wear monitoring during turning (Iwata and Moriwaki 1977, Emel and Kannatey-Asibu 1988, Rangwala and Dornfeld 1990, Waschkies *et al.* 1994). However, AE signals are highly dependent on cutting conditions, tool and workpiece material/geometry, etc., and therefore require trial cuts in order to determine a proper model. Additionally, AE signals often have to be treated with additional signal processing schemes to extract the most useful information to monitor tool wear condition. Location of the AE sensor is also a very difficult problem when applied to machine tools.

The performance of monitoring systems based on cutting force and AE are still far behind expectations, the primary reason being its high cost/performance ratio (Stein and Huh 1991). In order to overcome these disadvantages, motor-current-based techniques were developed to monitor tool wear condition, these being the simplest alternative in technical terms and also very simple to retrofit (Byrne *et al.* 1995). In this paper, we propose a system based on feed-motor current for on-line estimation of tool wear rate, $\dot{w}$, and, consequently, monitoring tool wear condition. A review of cutting literature reveals that the cutting current is mainly a function of tool flank wear, w, under fixed cutting conditions. In turn, the tool wear rate, $\dot{w}$, depends on the cutting current. The present paper describes a method of calculating the tool wear rate from a well-recognized mathematical model using feed cutting current. Based on a knowledge of the feed cutting current, we determine whether the tool wear has accelerated and, thus, whether the tool has reached the final stages of its useful life.

2. Feed drive system

2.1. *Modelling of the feed drive system*

A typical AC servo feed drive system on a CNC lathe is composed of the following basic components: cutting tool, tool post and carriage, ball screw, bearings supporting the ball screw, feed box, feed motor and lubrication system. A simple model of the feed drive system consisting of these mechanical components is shown in figure 1 (Li, Venuvinod and Chen 2000). In the model, the inertias of all moving parts are lumped into an equivalent inertia, J. Likewise, the overall viscous damping in the absence of the cutting load is lumped into an equivalent viscous damping with

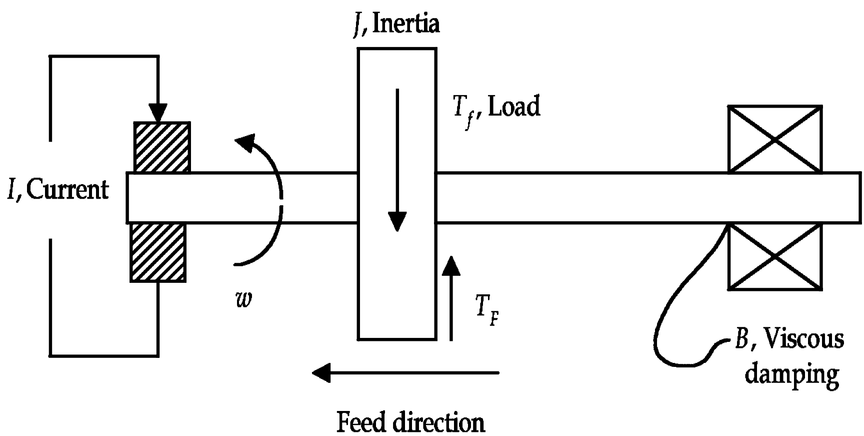

Figure 1. A simple model of the typical feed drive system.

damping coefficient, B. The additional viscous damping caused by the cutting forces and the total try or coulomb friction are accounted for by a friction torque, T_F. Finally, the feed force component is represented as a generalized disturbance torque on the feed motor, T_f.

In steady state, the equation of motion of the feed drive system can be expressed as:

$$KI = Bw + T_F + T_f, \tag{1}$$

where w is the angular velocity and K is the feed–motor constant. The friction torque T_F can be expressed as:

$$T_F = T_{F0} + \Delta T_F + \Delta T_v, \tag{2}$$

where T_{F0} is the coulomb friction torque in the air cutting condition and ΔT_F and ΔT_v are the additional coulomb and viscous friction torques due to the cutting load, respectively.

The feed force, F_f, and its corresponding torque, T_f, in equation (1) are functionally related:

$$T_f = \frac{p}{2\pi\mu} F_f, \tag{3}$$

where μ and p are the mechanical efficiency and pitch (length/rotation) of the ball screw, respectively. Substituting (3) into (1), it becomes apparent that the feed force, F_f, depends on the motor drive current, I.

Force F_f (or torque T_f) in (1) will be estimated based on the corresponding 'cutting current', $\Delta I = I - I_0$, where I is the magnitude of the measured total current and I_0 is the 'air cutting current' that is consumed when there is no cutting load.

In the case of air cutting, following (1), we have $KI_0 = Bw + T_{F0}$. By subtracting this expression from (1), it follows that

$$K\Delta I = \Delta T_F + \Delta T_v + T_f. \tag{4}$$

Because the air cutting current I_0 has been estimated before cutting, the cutting current $\Delta I = I - I_0$ can be calculated from the measured value of the total current, I. On the other hand, since the additional friction torques, ΔT_F and ΔT_v, depend on the feed cutting force and feed speed, the feed force, F_f, can be expressed as function (initially unknown) of ΔI and f:

$$F_f = F(\Delta I, f). \tag{5}$$

Equation (5) indicates that it is important to recognize that the feed cutting force depends on the cutting current and feed speed. At fixed feed speed, the relationship between the feed cutting force and feed cutting current is linear, a conclusion verified by Stein *et al.* (1986), Altintas (1992), Lee *et al.* (1995) and Kim and Kim (1996).

2.2. *Measurement of feed-motor current*

Measurement of feed-motor current was performed on a CNC turning centre with permanent magnet AC synchronous motors. The measurement instrument for feed-motor current is shown in figure 2. Three current sensors (Hall Effect Current Transducer, Stock No. 286-327) are used to obtain the feed-motor current I_{rms} signals. The three-phase feed-motor currents I_U, I_V, and I_W are measured by three current sensors, and through a low-pass (50 Hz) filter. In DC servo drive systems, the

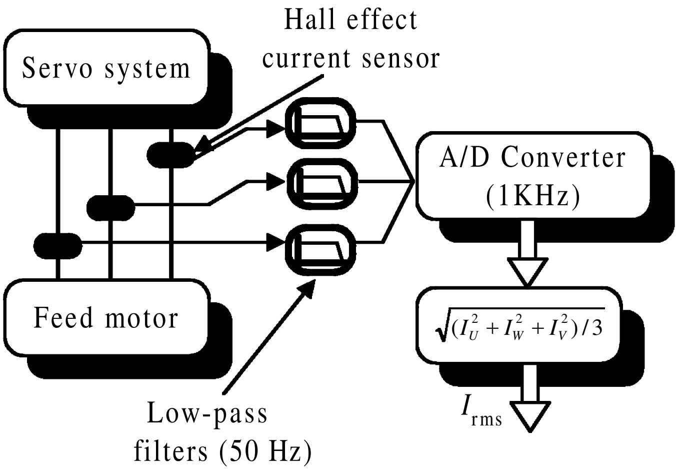

Figure 2. Schematic diagram of feed-motor current measurement.

motor torque (T) is given by DC current multiplied by motor torque constant (K). In an AC servo drive system with three-phase synchronous motors, equivalent DC currents are derived from the three-phase AC currents. One of the methods for converting AC current to equivalent DC current is the D–Q transformation. However, another method, which is very simple and widely used in industry, is to use the root mean square (RMS) value to convert AC current to the equivalent DC current, as shown in equation (6).

$$I_{rms} = \sqrt{\frac{1}{3}(I_U^2 + I_V^2 + I_W^2)}. \tag{6}$$

3. Tool wear model

It has been recognized widely that tool life can be divided into three phases characterized by three different flank wear processes: (i) break-in, (ii) normal wear and (iii) abnormal or catastrophic wear (figure 3). The sudden rise in wear rate observed during the abnormal tool wear phase (phase iii) is of interest here as an indication of the need for tool replacement. Because many factors affect tool wear, the wear curve usually fluctuates and is not smooth.

For practical tool monitoring, the wear amount during the normal phase, w, is expressed as the sum of two parts. The first part is the determinable linear increase $\dot{w}t$ that is superimposed onto the second, w_0:

$$w = w_0 + \dot{w}t, \tag{7}$$

where w (mm) is the flank wear value, w_0 (mm) is the initial flank wear during normal phase, $\dot{w}$ (mm/min) is the flank wear rate in the second phase, and t (min) is the cutting time.

The objective in this paper is to monitor the rise in the wear rate $\dot{w}$ associated with the final stage of the accelerated tool wear in phase (iii) (figure 3) so that a tool replacement decision could be made. We propose that this be achieved indirectly by monitoring the feed-motor current, I, that is related to the tool wear, w, through the feed cutting force, F_f. Note that it is not necessary to know the two functional

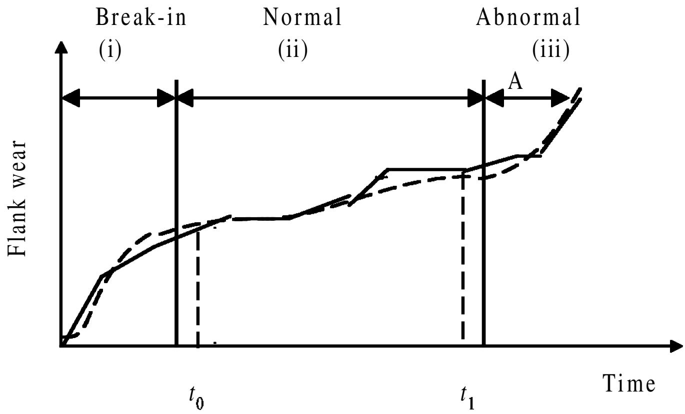

Figure 3. Tool wear phases.

dependencies required exactly since only the onset of the sudden rise in the rate of change (acceleration) is intended to be detected.

First of all, we need to analyse the relationship between the feed cutting force and flank wear. Numerous researchers have studied the cutting process and proposed models for tool wear; for example, Park and Ulsoy (1992) proposed that flank wear dominates the tool process in many important applications, and proposed the following model for this component of tool wear:

$$F_f = k_1 f^n d + k_2 v d + k_3 d + k_4 d w, \tag{8}$$

where F_f is the feed cutting force, and is the output for the system; w is the flank wear, f, v, d are the feed, cutting speed, and depth of cut, respectively, and are the inputs for this system. n and k_i are constants which depend on the effective rake angle, workpiece material, and other task-related parameters. Therefore, under fixed cutting conditions, the feed cutting force is directly proportional to flank wear, as shown:

$$F_f = K_1 w + C_1. \tag{9}$$

Based on (5), the feed cutting force is linearly related to feed cutting current under fixed cutting conditions, i.e.

$$F_f = K_2 \Delta I + C_2. \tag{10}$$

Combining (10) and (9), the relation between feed cutting current and flank wear under fixed cutting conditions during turning is shown as follows:

$$\Delta I = K_0 w + C_0. \tag{11}$$

Note that equation (11) holds in the second phase, namely the normal flank wear phase. Hence, the dependence of the feed cutting current on flank wear can be modelled in this specific context as a linear function:

$$\Delta I = \Delta I_0 + K w, \tag{12}$$

where ΔI_0 is the feed cutting force arising under identical cutting conditions but with an un-worn cutting tool (i.e. when $w = 0$) and K is a parameter dependent on cutting conditions such as cutting speed v, feed rate, f, and depth of cut, d.

Combining equations (7) and (12), we obtain

$$\Delta I = \Delta I_0 + K w_0 + K \dot{w} t. \tag{13}$$

Differentiating the terms in equation (13), we can express the change in feed cutting current, $\Delta I'$, as

$$\Delta I' = K \dot{w} \Delta t, \tag{14}$$

thus

$$\dot{w} = \Delta I' / K \Delta t. \tag{15}$$

It follows from equation (15) that the detection of a noticeable change in the calculated wear rate $\dot{w}$ should, in principle, indicate that the tool is in its final stage of accelerated wear (phase (iii) of figure 3) and should be replaced. In reality, however, the wear rate thus calculated fluctuates since the cutting current ΔI includes noise. This complicates evaluation of the normal value of wear rate needed as a reference while establishing the onset of the further abnormal increase.

4. Monitoring algorithm

In order to evaluate the normal tool wear rate based on equation (15), a sufficiently long time interval $\Delta t = N\tau$ is required, where N is an adjustable integer multiplier and τ is the fixed time-base (program scan time) used in the calculations. We select the multiplier N based on prior experience such that this time interval $\Delta t = N\tau$ would be stretched to correspond to the shortest expected normal tool wear phase. The actual monitoring starts with the 'normal' wear rate thus established as the reference. Each newly calculated wear rate is compared to such a reference regarded as the threshold: a repeatedly high difference between the two indicates abnormal tool wear and a need to change the tool (figure 4).

It is difficult to determine the threshold value implicit in the measurements. For this reason, a trend factor $T_s(n\tau)$ for the tool wear rate $\dot{w}$ at some instance in time t_0 is defined as

$$T_s(n\tau) = \dot{w}_{t_0+n\tau} - \dot{w}_{t_0}, \tag{16}$$

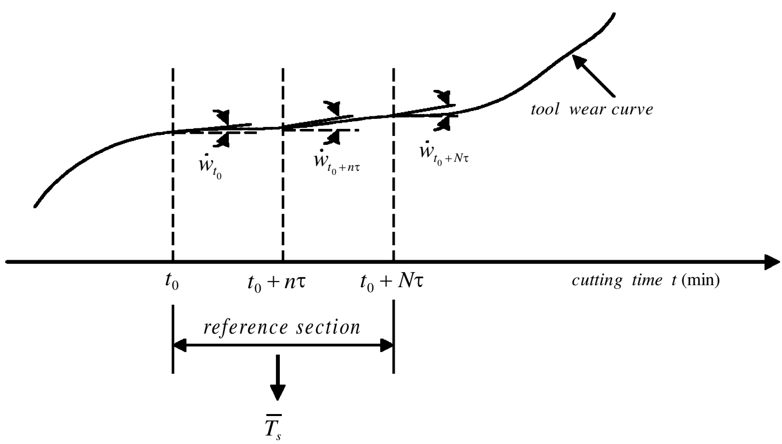

Figure 4. Schematic diagram of the monitoring strategy.

where n is an integer $1 \leq n \leq N$. The average of such trends over all possible values of n can be defined as

$$\bar{T}_s = \frac{\sum_{n=1}^{N} T_s(n\tau)}{N}. \tag{17}$$

Finally, when the tool is in its normal wear state, the reference threshold is expressed as

$$T_T = C\bar{T}_s + \dot{w}(t_0), \tag{18}$$

where C is a constant determined by the experiments. Once this threshold has been determined, it is used to monitor the tool wear condition: when the excess of tool wear rate $\dot{w}$ over this threshold value T_T is registered repeatedly, the tool is judged to enter its abnormal wear state and has to be replaced.

5. Experiments and discussions

5.1. *Experiments*

Figure 5 shows a schematic diagram of the experimental setup used. Tests on a CNC lathe (Hitachi Seiiki, Hitec-Turn 20sII) were performed over a range of cutting conditions. The AC feed-motor current was measured using three Hall effect sensors. Signals obtained were low-pass filtered (with a cut-off frequency of 50 Hz) and A/D converted (sampling frequency: 1 kHz) for processing by a personal computer. The workpiece material was XW-5, HB 250 and the tool used was DNMG 15 06 04-QM, H13A. All tests were conducted under dry conditions.

In order to illustrate the processing of the proposed method, a test was conducted at a cutting speed 100 m min^{-1}, feed rate 0.1 mm rev^{-1} and depth of cut 2 mm. The feed-motor current over time was recorded at two-minumues intervals, and tool flank wear values were simultaneously measured by a microscope. These results were shown in figure 6. The change of feed cutting current with time was used to monitor flank wear rate. After some 24 minutes of cutting (tool wear 0.49 mm), the onset of accelerated wear (phase (iii)) can be noticed. Our system detected such an event by evaluating the wear rate and by comparing it with its pre-calculated threshold value as illustrated in figure 7. From this figure, it can be noticed that the tool wear rate increases quickly as soon as the tool enters the abnormal wear phase. In this example, the threshold value was calculated at $T_T = 0.033$. Other parameters were $T_S = 0.0083$, $C = 2$, $\dot{w} = 0.0167$ mm min^{-1}.

5.2. *Discussions*

Although dynamometers can provide accurate measurements of cutting forces and monitor tool wear conditions during turning, their application in tool monitoring is not practical. At the cost of more complex computer processing, sensing motor current of the feed drive represents a much better alternative in terms of equipment cost, unobtrusiveness, non-interference around the working zone, retrofitting and hardware simplicity. On the other hand, one limitation of this current-measuring approach is that it cannot be applied to light cuts because the magnitude of the useful signal is then too small and difficult to extract from the total current measured. This total current fluctuates in accordance with the lubrication state and

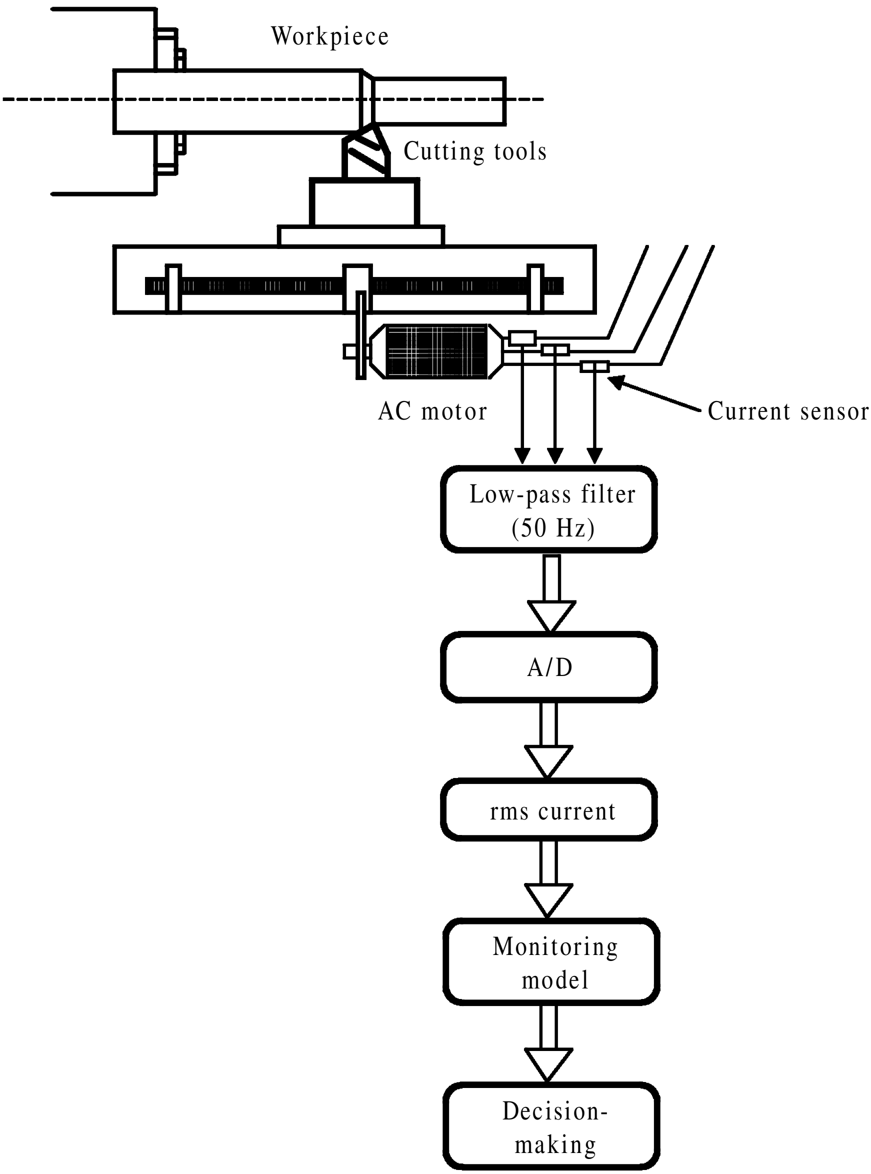

Figure 5. Schematic of the experimental setup.

traversa rate of the guideway. However, in such cases, the need for tool monitoring is also reduced.

The method described does not rely on an exact measurement of the feed cutting current, but on an indication of its relative change (gradient). Hence, the fact that the feed cutting current is estimated with up to 10% inaccuracy is not detrimental to tool monitoring. Moreover, since the wear process is slow in comparison to the time required for execution of the program loop, multiple verifications of the decision to replace the tool can be afforded to provide increased confidence in the decision made.

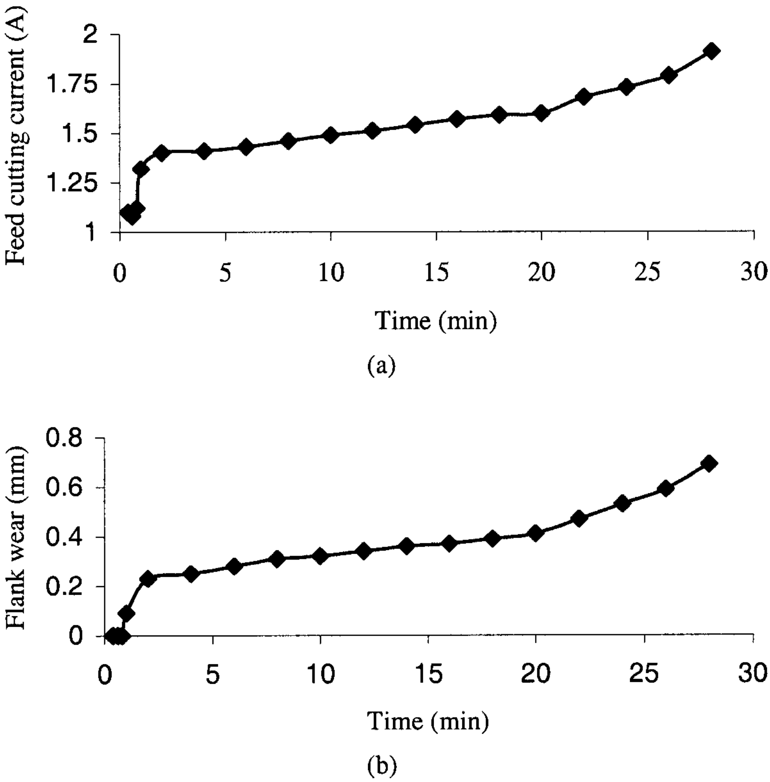

Figure 6. Observed feed-motor current and tool wear with time.

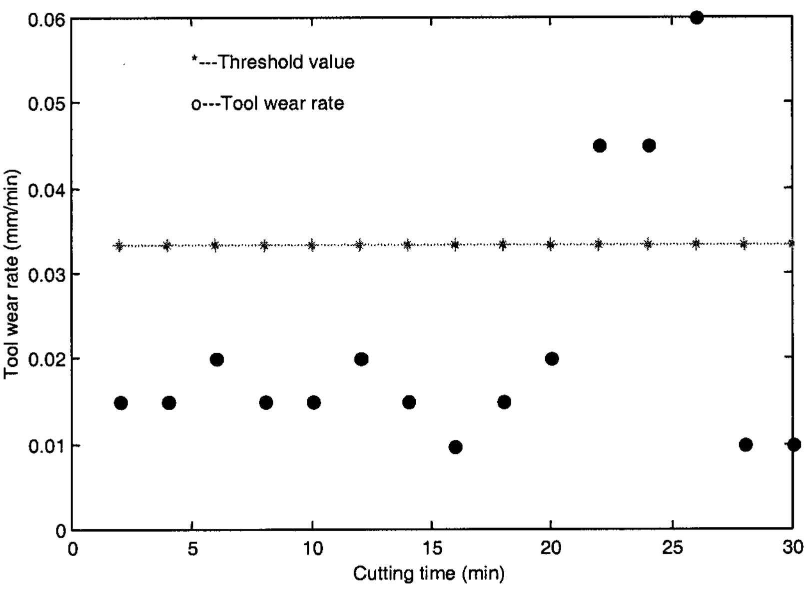

Figure 7. Observed tool wear rate with time.

No.	v (m min^{-1})	f (mm rev^{-1})	d (mm)	Flank wear (mm)
1	100	0.2	1	0.454
2	100	0.2	1	0.606
3	100	0.2	2	0.494
4	100	0.1	1	0.667
5	100	0.3	1	0.578
6	150	0.2	1	0.573
7	200	0.3	1	0.606
8	75	0.25	1.5	0.496
9	75	0.2	1.5	0.597
10	75	0.3	1.0	0.588
11	75	0.4	1.0	0.574
12	100	0.15	1.5	0.572
13	100	0.2	1.5	0.584
14	100	0.25	1.5	0.855
15	100	0.3	1.5	0.577
16	100	0.15	1.5	0.568
17	100	0.15	1	0.499
18	100	0.2	1	0.518
19	100	0.25	1	0.520
20	75	0.2	1.5	0.554
21	75	0.25	1	0.466
22	75	0.25	1.5	0.473
23	75	0.15	1.5	0.481
24	75	0.2	0.5	0.516
25	125	0.25	0.5	0.536
26	125	0.3	0.5	0.494
27	125	0.35	0.5	0.523
28	100	0.35	1	0.616
29	100	0.25	1	0.625
30	100	0.15	1	0.561

Table 1. Conditions for experiments and flank wear.

Whatever the cutting conditions and tool and workpiece material, the threshold value for the feed cutting current gradient is calculated first during the period of known normal tool wear. Only then is the floating threshold value thus established used in the monitoring process. Such an approach allows the flexibility of self-adaptation across a variety of cutting conditions, work and tool materials.

Thirty tests with different cutting conditions were used to verify the performance of the proposed monitoring system. Flank wear rate was monitored by using feed cutting current, with large changes of flank wear rate indicating that the cutting tool had entered phase (iii), generating the need to send a command to stop machining and replace the worn tool. After the tool was removed from the machine, the amount of flank wear was measured by microscope. The conditions used for the experiments and the flank wear amount measured are listed in table 1. It can be observed that the proposed monitoring system gave a percentage correct classification of 93.33% when the range of flank wear was determined to be between 0.45 mm and 0.65 mm.

6. Conclusions

A real-time tool wear condition monitoring system for turning operations is proposed, using feed-motor current. The functional dependence of feed cutting current on tool wear has been analysed and expressed in the form of a difference equation relating the variation of feed cutting current to tool wear rate. By comparing successive feed cutting currents, the onset of accelerated tool wear can be determined so that a request for tool replacement can be issued. The method is, in principle, capable of being adapted to a wide range of cutting conditions, workpiece and tool materials. Experimental results have shown that this method of tool wear condition monitoring is effective, simple, low-cost, and industrially applicable.

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