Int J Adv Manuf Technol (1999) 15:305–310

The International Journal of Advanced Manufacturing Technology

Real-Time Monitoring of Tool Fracture in Turning Using Sensor Fusion

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The sensor fusion method using both an acoustic emission (AE) sensor and a built-in force sensor is introduced for on-line tool condition monitoring during turning. The cutting force was measured by a built-in piezoelectric force sensor, which was inserted in the tool turret housing of an NC lathe. FEM analysis was carried out to locate the most sensitive position for the sensor. A burst of AE signal was used as a triggering signal to inspect the cutting force. A significant drop in cutting force indicated tool breakage. The algorithm was implemented in a DSP board and the monitoring system was installed on a CNC lathe in an FMS line for in-process tool-breakage detection. The proposed system showed an excellent monitoring capability.

Keywords: Acoustic emission; Built-in force sensor; Sensor fusion; Turret housing

1. Introduction

In-process detection of cutting tool breakage is important for the automation of a machining process. To prevent possible damage to the workpiece and machine tool, reliable sensing techniques are required in order to provide a rapid response to an unexpected tool failure. These sensing techniques will play an important role in the development of systems for the future factory [1]. Martin et al. [2] reported that cutting force is more sensitive to chipping and fracture than vibration and motor current. Lan and Dornfeld[3] reported that both tangential and feed forces are sensitive to tool fracture but only the tangential force decreases consistently when a tool breaks. Colwell and Mazur [4] analysed the pattern and duration of cutting force signals when a tool breaks, and developed a tool-breakage detection algorithm. Brinksmeier [5] proposed an eddy current sensor in drilling for the in-process measurement of torque at the drill shank. It was reported that tool fracture could be predicted because a large dynamic signal can be detected shortly before the breakage. Iwata and Moriwaki [6, 7] proposed a tool-breakage detection method using an acoustic emission (AE) signal. Kannatey-Asibu and Dornfeld [8] derived a theoretical relationship between acoustic emission and machining parameters. A new parameter describing the characteristics of the cutting process was proposed by Inasaki et al. [9] to eliminate the interference effect of randomly occurring burst-type AE signals. Blum and Inasaki [10] summarised the relationship between AE signals and machining parameters. Emel and Kannetey-Asibu [11] developed a method to detect tool breakage using the spectra of AE signals based on pattern recognition. Inasaki and Yonetsu [12] reported that a stepwise increase of the AE signal was observed after tool fracture. He attributed the increase of the AE signal to a sudden increase of the contact area between the workpiece and the cutting tool. Lan and Dornfeld reported that a burst of AE signals due to tool fracture was generated and the amplitude of the r.m.s. AE value was proportional to the fracture area. Youn et al. [13] observed and analysed various patterns of AE signals and cutting forces in various aspects of tool fracture.

Most research, based on cutting force measurement by a tool dynamometer, may not be applicable to a production environment because of the alteration of the machine tool dynamics. Moreover, a tool dynamometer is not economical for industrial use. To overcome these difficulties, a built-in piezoelectric force sensor is used in this work to measure the cutting force during turning. Since the piezoelectric force sensor can be installed in the machine tool structure away from the cutting tool, not only can the alteration of the machine tool dynamics be avoided, but also the harmful effects from chip and lubricant. The sensor fusion concept is also introduced for using an AE sensor and a built-in force sensor simultaneously. Chip formation, runout and variations in speed and depth of cut can generate AE or force signals, which are similar to those arising from tool breakage [14]. Usage of both sensors

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ensures avoidance of faulty detection of tool breakage and also permits practical usage in a production environment.

2. Determination of the Built-in Force Sensor Position

The location of the force sensor has to meet the following conditions. First, it has to be installed at a location where the sensitivity of the measured signal to the variation of the cutting force is as high as possible. Secondly, the sensor must not interfere with any job in the production environment. Use of a tool dynamometer may cause not only a limitation of the workpiece size, but also difficulty in installing the workpiece. The built-in force sensor must be installed in a suitable place to avoid these problems. Thirdly, the sensor must not be affected by tool changes during the machining process. A CNC lathe, which uses different tools, is equipped with a turret or an automatic tool changer. If the sensor is installed on the rotating part, the distance between the tool–workpiece contact point and the sensor position, changes whenever the turret rotates. As a result, the stress measured by the sensor varies, even when the cutting force does not change. So the sensor must not be installed on the moving or rotating part.

The second and the third conditions conflict with the first condition. To satisfy the second and the third conditions, the turret housing, instead of the turret, is selected for building in the force sensor installation. FEM analysis is carried out to find the best position for the sensor mounting. The turret housing is modelled as a rigid body. An analysis with MSC/NASTRAN FEM software is performed when a concentrated cutting force is applied at the tool tip. The turret housing is made of cast iron (GC 25) with a Young's modulus of 70 GN/m^2 and a Poisson ratio of 0.3. The normal stress in the Z-direction in the turret housing owing to the cutting force is shown in Fig. 1. As shown in the figure, the normal stress is concentrated around the corner of the turret housing support. Consequently, the best position for the built-in force sensor is determined to be the point near the first bolt. After determination of the best position for the force sensor, the transmission ratio between the cutting force and the stress measured by the built-in force sensor is determined experimentally. The experiments are designed to find the effects of cutting speed, feedrate and depth of cut on the transmission ratio. Figure 2 shows the variation of cutting force and transmitted force according to cutting speed (feedrate: 0.15 mm/rev, depth of cut: 2 mm), feedrate (cutting speed: 230 m/min, depth of cut: 2 mm), and depth of cut (cutting speed: 230 m/min, feed rate: 0.3 mm/rev). From the experiments, the attenuation ratio is determined to be 5.4.

3. Variation of Cutting Force and AE Signal Due to Tool Fracture

Preliminary tool-breakage experiments to determine the relationship of cutting force and AE signal were carried out on a CNC lathe (DAEWOO PUMA-10S). The experimental set-up for tool-condition monitoring in turning is shown in Fig. 3. An AE sensor (NF Co. AE-905US) is attached at the back of the tool shank by a magnetic holder which can be easily mounted and dismounted by a robot. A discriminator (NF Co. AE-922) is used to determine the signal envelope of the fast changing AE signal. Since the power spectrum due to tool fracture is in the range of 100 kHz–1 MHz, a bandpass filter of 100 kHz–1 MHz transmission frequency is used to filter out unnecessary signals from the AE sensor. A low-pass filter with a 3 kHz cut-off frequency is used to measure the

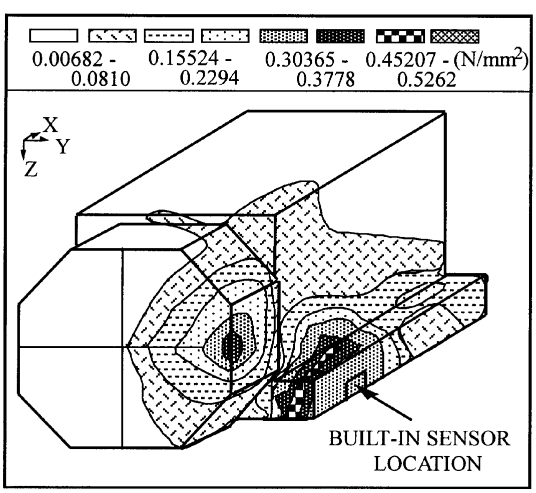

Fig. 1. Normal stress (in Z-direction) distribution when cutting force is applied at the tool tip.

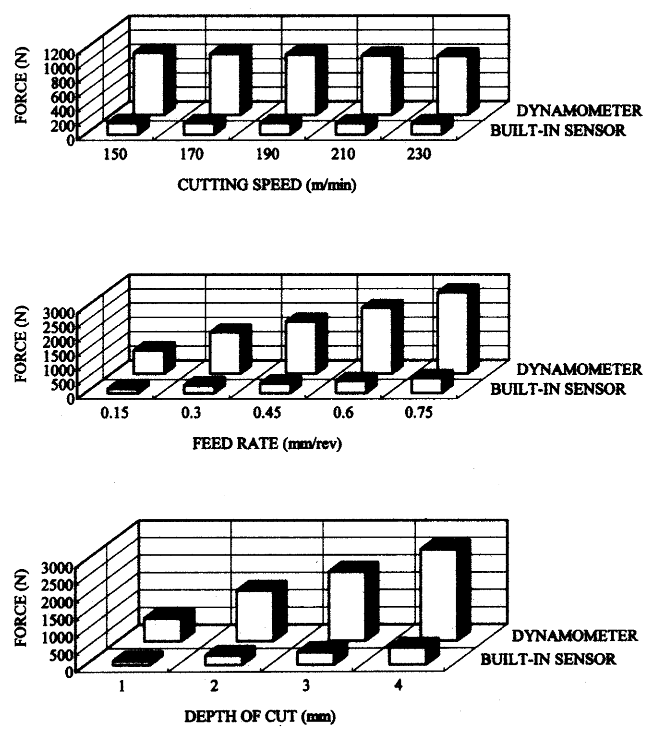

Fig. 2. Variation of cutting force and transmitted force according to cutting speed (feedrate: 0.15 mm rev^{-1}, depth of cut: 2 mm), feedrate (cutting speed: 230 m min^{-1}, depth of cut: 2 mm) and depth of cut (cutting speed: 230 m min^{-1}, feedrate: 0.3 mm rev^{-1}).

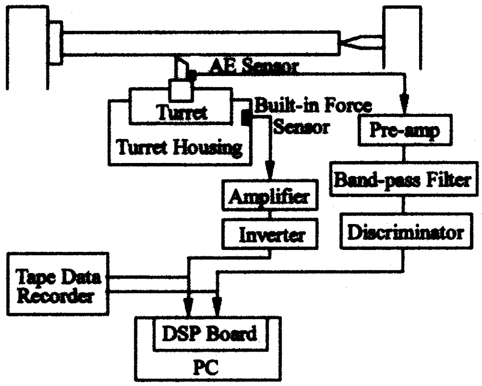

Fig. 3. Schematic diagram of experimental set-up.

force signal using a built-in force sensor. Two kinds of experiment were performed to detect the relationship of the force signal and the AE signal, when a tool breaks. In the first group of experiments, tungsten carbide insert tips were slotted by wire EDM on the rake face to accelerate fracture. In the second group of experiments, tungsten carbide bits were inserted and brazed to the workpiece to induce tool breakage during machining. The material for the experiments was S45C steel for the workpiece and tungsten carbide (CNMG 120408, P20) for the inserts. All experiments were conducted under dry cutting conditions.

For the first group of experiments, which were conducted with slotted inserts, cutting speed and depth of cut were kept constant during machining, while feedrate was gradually increased. Many experiments under different cutting conditions were carried out in the cutting speed range of 100–250 m/min and the depth of cut range of 0.5–3 mm. The cutting conditions for the second group of experiments were set to 200 m/min cutting speed, 2 mm depth of cut, and 100 mm/min feedrate. The results of the first group of experiments with slotted inserts are shown in Fig. 4. A significant drop in the cutting force follows the AE signal burst. It can be seen that the cutting force is reduced from 1000 N to about 200 N because the broken tool cuts a small part of the workpiece right after breakage. In one revolution of the workpiece, another chipping is observed. In two revolutions, the shim of the tool holder starts to participate in cutting, which accounts for the increase of cutting force. This tendency is shown in all experiments which were conducted more than 50 times and is consistent with the results in the literature [3].

Figure 5 shows the results of the second group of experiments. The cutting force drops periodically when the tool cuts the brazing material between the workpiece and the inserted carbide bit. Also, a periodic AE burst is observed when the tool cuts through the brazing material A large burst of AE signal occurs when the tool collides with the embedded carbide bit in the workpiece. A significant drop of cutting force follows the burst of AE signal when the tool breaks. SEM photographs of broken inserts in both experiments are shown in Fig. 6. The broken insert with the EDM slot shows a clear cleavage and the broken insert which collided with the embedded carbide is damaged severely on both major and minor cutting edges. From both experiments, it is shown that a significant drop of cutting force is observed after a burst of AE signal when a tool breaks.

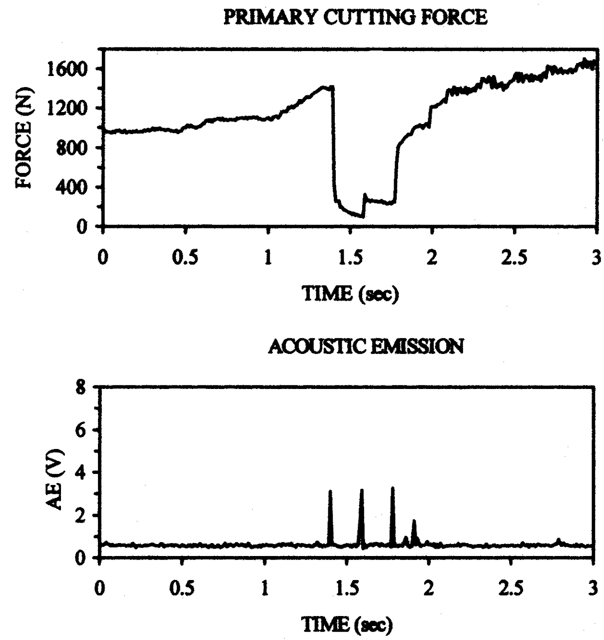

Fig. 4. Cutting force and AE signal in turning. Cutting speed: 100 m min^{-1}, depth of cut: 1.0 mm (using slotted insert).

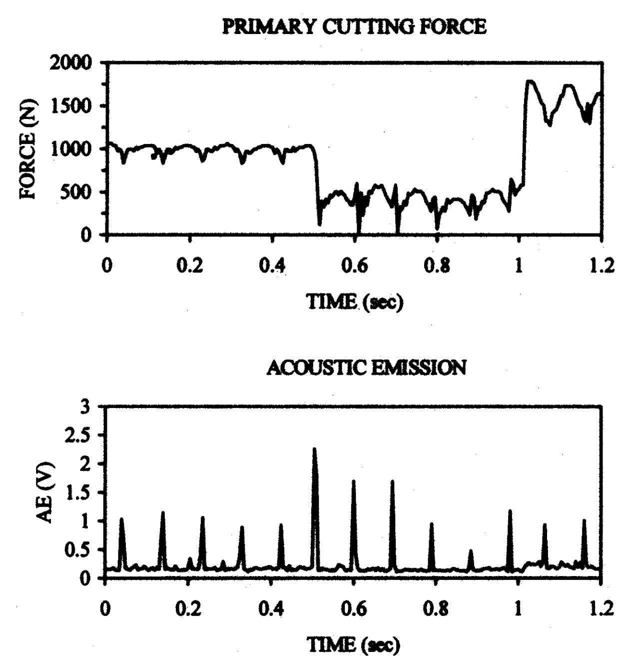

Fig. 5. Cutting force and AE signal in turning. Cutting speed: 200 m min^{-1}, depth of cut: 2.0 mm, feedrate: 100 mm min^{-1} (using workpiece embedded carbide).

4. Tool Breakage Detection Algorithm

Acoustic emission is generated during a variety of metal cutting processes. Since acoustic emission is the transient elastic energy

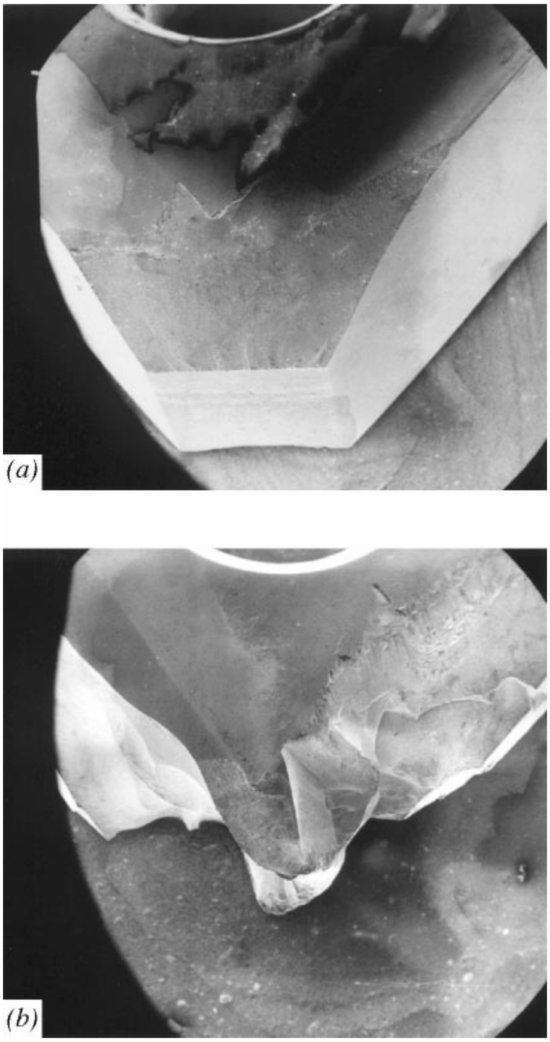

Fig. 6. SEM photographs of broken inserts: (*a*) fractured insert with EDM slot and (*b*) fractured insert collided with the embedded carbide.

released in materials undergoing deformation and fracture, various sources of AE can be identified in metal cutting [3]. Acoustic emission is generated at any time during normal machining. However, there are distinct differences between the amplitudes of AE signals obtained during fracture, chipping and normal machining [7, 9]. This makes it possible to monitor tool fracture with an AE sensor by setting an appropriate threshold. Since the threshold is a function of the machining parameters, an attempt was made to relate the AE signal and cutting parameters [8].

As shown in the previous section, when a tool breaks, the cutting force increases slightly immediately after tool breakage and then decreases sharply. The reason for the cutting force increment is considered to be instant jamming of broken debris between the tool and the workpiece. Then, the cutting force drops because of the complete break-up of the tool. The change of cutting force itself can be a good indicator for the detection of tool breakage. However, the cutting force is also a function of the machining parameters, and it changes as the cutting conditions change. By comparing the AE signal with the cutting force signal, it was found that AE signal burst occurs immediately before the sharp drop of cutting force [3]. This observation is used for tool-breakage detection in this work. A burst of AE signal triggers the examination of the cutting force to detect tool breakage. If the cutting force drops sharply after the burst of AE signal, it can be regarded as tool breakage. Otherwise, it is a part of normal machining. When the tool encounters a pocket or a hole in the workpiece, the cutting force drops suddenly. However, a burst type AE signal is not observed in this case. During the normal engagement or disengagement of the tool, the cutting force changes gradually. If the tool breaks at the very first contact with the workpiece, tool breakage cannot be detected.

This scheme is implemented in a digital signal processing (DSP) board in a personal computer. First, the system detects a burst-type AE signal, which triggers the cutting force monitoring. Important factors to consider at this stage are the reduction of noise from other sources and the distinction between burst-type AE signals and normal AE signals. The following steps are used to identify an AE burst (Fig. 7).

1. The average value of the AE signal is calculated in a block. One block consists of N number of digital AE data items. The average AE level per block, $AE\_avg[t]$, and the cumulative block AE average (the average of these block averages), AE_n, are calculated

$$AE\_avg[t] = \left(\sum_{i=1}^{N} AE[i]\right) \Big/ N \tag{1}$$

$$AE\_n = \left(\sum_{t=1}^{n} AE\_avg[t]\right) \Big/ n \tag{2}$$

   where $AE[i]$ (i=1, n) is the AE signal measured between times t and t+1, and n is the number of blocks.

2. The duration of the burst-type AE signal due to tool fracture in turning was found, from experiments, to be approximately 1 ms. When the sampling frequency is f kHz, the block comparison index, $AE\_max[t]$, is defined as the average of the largest f signals of N data in one block.

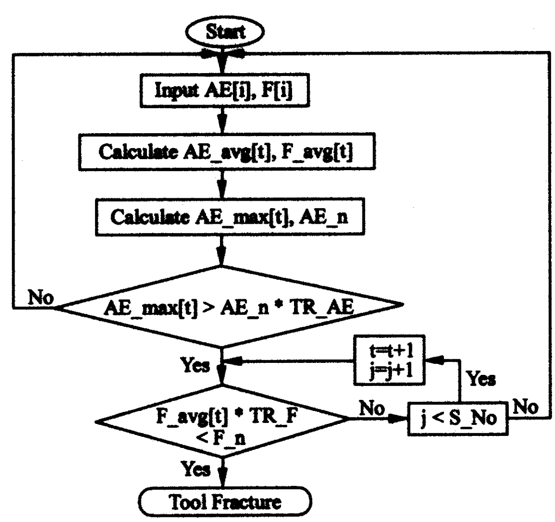

Fig. 7. Tool-breakage detection algorithm.

3. The algorithm compares the block comparison index, $AE\_max[t]$, with the cumulative block average, AE_n. If $AE\_max[t]$ is larger than AE_n*TR_AE, it is considered to be a burst-type AE signal. The threshold of the AE ratio, TR_AE, is determined from experiments.

Secondly, the algorithm monitors the cutting force to determine whether the burst-type AE signal is from tool fracture or is other unexpected noise. The burst-type AE signal due to tool fracture is followed by a sudden decrease of cutting force.

1. Average force per block, $F\_avg[t]$, is calculated.

$$F\_avg[t] = \left(\sum_{i=1}^{N} F[i]\right) \Big/ N \tag{3}$$

2. When the burst-type AE signal is observed in block t, the algorithm sets the reference force, F_n, to $F\_avg[t-1]$ and compares the current block average, $F\_avg[t]$, with F_n. If $F\_avg[t]$ is less than F_n/TR_F, it is considered as tool breakage. TR_F is the threshold of cutting force ratio to be determined experimentally. When $F\_avg[t] > F\_n/TR\_F$, compare $F\_avg[t+j]$ with F_n (where $j=1,2,\ldots$) until the searching time (S_No) is over. The searching time (S_No) is a finite time in which the cutting force is monitored. A sudden decrease of the cutting force due to tool fracture does not always take place in one block after a burst of AE signals. From experiments, the force drop occurred within 0.02 s of the AE burst for turning. A proper threshold of cutting force ratio in turning, TR_F, should be determined experimentally.

For every 20 sets of input and output data, the block comparison index, $AE\_max[t]$, is calculated and compared with the cumulative AE average, AE_n. The ratio of $AE\_max[t]$ to AE_n is defined as R_AE. For cutting force signals, for every 20 sets of input data, which corresponds to 5 ms for a 4 kHz sampling rate, the average force, $F\_avg[t]$, is calculated and compared with the cumulative block force average, F_n to determine the ratio $R\_CF=F\_n/F\_avg[t]$. A burst of R_AE is followed by a burst of R_CF in the case of tool breakage. The monitoring time of R_CF after a burst of R_AE is determined to be 0.02 s, which corresponds to 4 blocks when 1 block is the time for 20 inputs. In most cases, a drop of cutting force occurred in 2 blocks after a burst of AE signal. In this work, the values of TR_AE and TR_F are set to be 5 and 2, respectively. When $AE\_max[t]$ is 5 times larger than AE_n, $F\_avg[t]$ is compared with F_n. It is determined to be tool breakage when $R\_CF=F\_n/F\_avg[t]$ is bigger than 2. The time taken to determine tool breakage must be as short as possible so as not to cause severe damage to either the workpiece or the machine tool. It takes 0.02 s to monitor tool breakage in the proposed tool condition monitoring system.

5. Tool Condition Monitoring System for a CNC Lathe

The developed tool condition monitoring system consists of a DSP board, a built-in force sensor and an AE sensor and was installed on a CNC lathe as shown in Fig. 8. In this scheme,

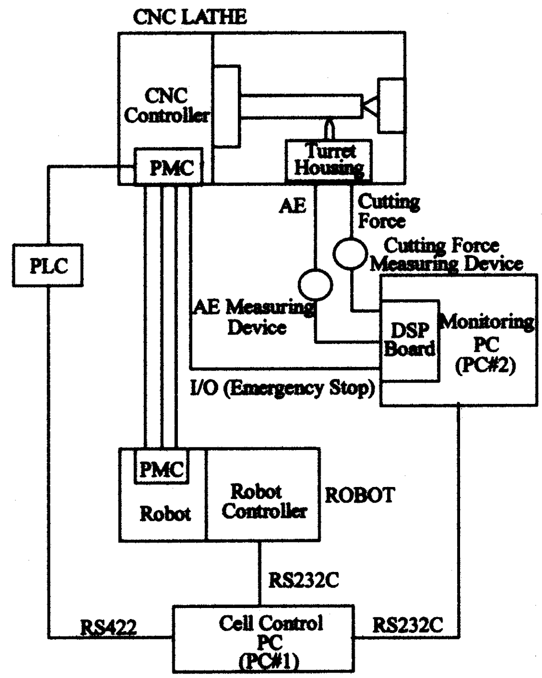

Fig. 8. Tool-breakage detection system for a CNC lathe.

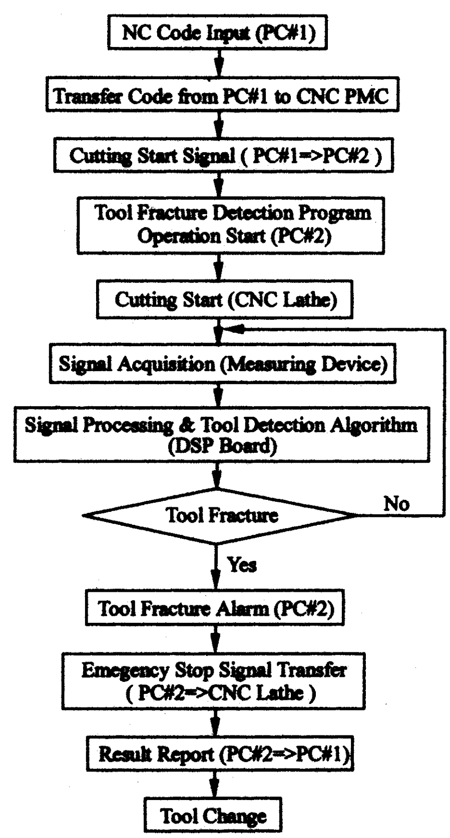

Fig. 9. Flowchart of tool-breakage detection system.

Table 1. Experimental results for system performance evaluation.

Cutting speed (m/min)	Depth of cut (mm)	Fracture	Detection
100	0.5	Yes	Yes
	1.0	Yes	Yes
	1.5	No	No
120	0.5	Yes	Yes
	1.0	Yes	Yes
	1.5	Yes	Yes
150	0.5	Yes	Yes
	1.0	No	No
	1.5	Yes	Yes
170	0.5	Yes	Yes
	1.0	Yes	Yes
	1.5	Yes	Yes
200	0.5	Yes	Yes
	1.0	Yes	Yes
	1.5	Yes	Yes

the main computer PC#1 controls the machining process and monitors the tool condition. PC#2 performs A/D conversion of the cutting force and the AE signal. A robot was used to load and unload the workpiece, mount the AE sensor, and change the chuck. PC#1 communicates with the CNC controller when tool breakage is detected. The AE signal and cutting force are measured by a DSP board in PC#2 and their chronological variations are shown on the console of PC#2 with other values used to determine tool fracture. Figure 9 shows the flowchart of the whole system. To evaluate the developed monitoring system, 15 experiments under different cutting conditions were carried out and the results are given in Table 1. To induce tool breakage, the feedrate was increased manually during experiments. Out of 15 experiments the tool broke 13 times and nothing happened in 2 cases. In all experiments, the developed system recognised the tool condition successfully.

6. Conclusions

A real-time tool-breakage detection system was studied in the turning process by the sensor fusion concept of an acoustic emission sensor and a built-in force sensor. To measure the cutting force without altering the characteristics of the machine tool dynamics, a built-in piezoelectric force sensor was used. It was found that the turret housing support close to the tool is the best place for the sensor mounting on a CNC lathe. Whenever a tool breaks, a significant drop of cutting force follows an AE signal burst. The AE signal burst was used as a triggering signal to examine the force change. If the force drops below the preset threshold, it was considered to be a tool breakage. In turning, the preset thresholds of the AE ratio and the cutting force ratio were set to 5 and 2, respectively. Tool breakage is time critical because it can cause fatal damage to the machine tool, workpiece and operator. The level tracking method of the time signal used in this work made it possible to recognise the tool fracture within 0.02 s in turning. The algorithm was implemented in a DSP board and a personal computer to detect tool fracture in process. Results showed that the proposed methodology worked very well for real-time tool-breakage detection. The developed monitoring system was installed on a CNC lathe in an FMS line, and it was confirmed that the proposed system predicted tool breakage reliably.

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Nomenclature

AE_avg[*t*]	average AE level per block
AE_n	cumulative block AE average (the average of these block averages)
N	number of items of digital data in one block
n	number of all blocks
AE[*i*]	digital AE data
AE_max[*t*]	the block comparison index, defined as the average of the largest *f* signals of *N* data in one block
F_avg[*t*]	the average force per block
F_n	reference force
TR_F	threshold of cutting force ratio
S_No	searching time
TR_AE	threshold of AE signal ratio
R_AE	ratio of *AE_max*[*t*] to *AE_n*
R_CF	ratio of *F_n* to *F_avg*[*t*]